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THE GENERAL
ELECTRIC CO. LTD.
OF ENGLAND

New Lighting for
Lloyds of London

Volume 25, number 4

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COVER PICTURE

The Underwriting Room in the new building of Lloyd's of London, for which the complete cold cathode installation and the majority of other lighting fittings were supplied by the G.E.C.

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New colour floodlighting at Niagara Falls.

Floodlighting at Niagara

THE combination of British technical skill in lighting with the natural beauties of Niagara Falls has produced a spectacle of a brilliance and variety which can challenge any other achievement of its kind. It was in the evening of June 20 that the sweeping panorama of the two Falls, separated by the rocky face of Goat Island, was seen for the first time as an ensemble in changing colours, which has already enhanced the reputation of Niagara as one of the major sightseeing attractions on the North American continent. The inauguration was performed by the Hon. George B. DeLuca, Governor of the State of New York, and the Hon. Charles Daley, Minister of Labour, Province of Ontario, who simultaneously pressed the switches which illuminated the American and the Canadian Falls respectively.

The previous floodlighting installation at Niagara had been in use for over 30 years and some deterioration in intensity had become perceptible. This led to mediocre performance when using colour screens. The screens had to be placed in position manually—in conditions often distinctly unpleasant for the operators in winter if the plume of spray from the Horseshoe Falls was being blown on to the searchlight platform and froze as it fell. Also, spray on the screens was boiled off by the heat of the lamp, causing wrinkling and rapid deterioration of the material. Renewal of the installation gave opportunities both for overcoming these drawbacks, and for replanning so that instead of the two falls being lighted individually, with the intervening Goat Island, the Rapids and the plume of spray hidden in darkness, the whole scene could be viewed as a continuous panorama in which the true magnitude of the falls would be assessed by comparison with familiar objects such as trees, buildings and people.

THE LIGHTING PLAN.

Months of study and development led to the award of the contract for the new lighting by the Niagara Parks Commission to the Canadian associate of the G.E.C., The Amalgamated Electric Corporation Ltd.

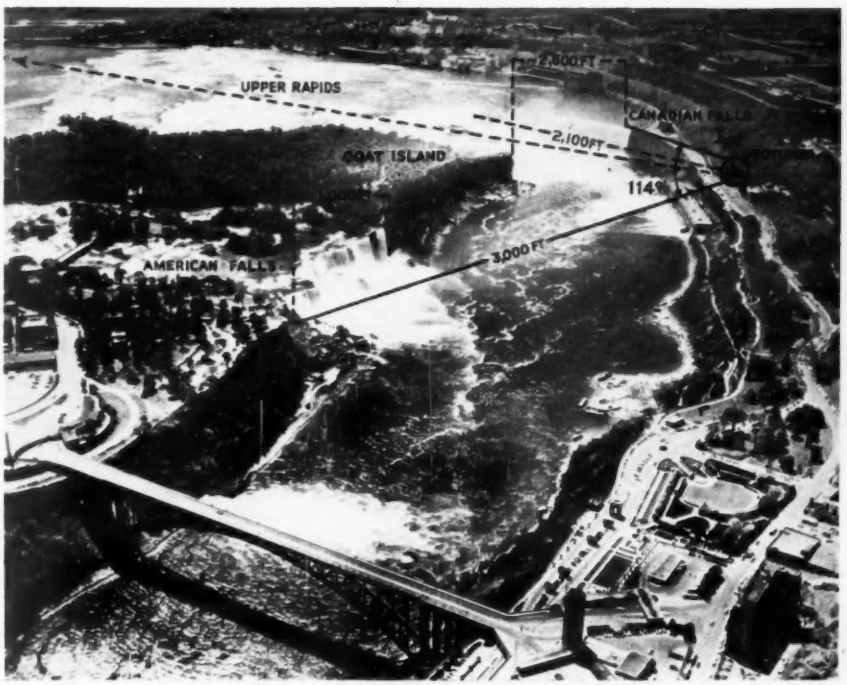


Fig. 1.—The American and Canadian Falls at Niagara.

The scheme put forward by the G.E.C. engineers who studied the problems on the spot retained the existing location for the floodlights on top of the surge tank building of the Niagara Falls power station. Expensive new heavy-current power cabling was thus avoided. This necessitated using long-range lighting as hitherto, and the change in lighting effect has been obtained by the use of several different beam shapes and a suitable arrangement of lighting patterns. These patterns are described in the table on this page and the location of the floodlights relative to the two Falls and other features is seen in fig. 1.

Fig. 2.—Prototype projector.

Arrangement of Floodlights

Part of Falls	Number of floodlights	Type of beam proposed
American	4	Fully focused horizontal fans arranged one above the other.
Bridal Veil	1	Fully focused soft edged beam.
Horseshoe : L.H.S. and R.H.S.	4 each	Fully focused horizontal fans arranged one above the other.
Spray plume	2	Fully focused vertical fans, side by side.
Rapids	2	One horizontal fan above crest. One fully focused hard edge narrow beam lighting up river.
Goat Island	3	De-focused horizontal fans side by side to cover full height of rock edge and link the two Falls.

It will be seen that 20 floodlights are used in the present installation. The previous number was 24, but the new lighting provides ten times the intensity and lights a larger area of the Falls and their neighbourhood without any increase in power consumption. Power is supplied from a 375 kW, 250 V d.c. motor-generator set in the Ontario power station downstream from the Horseshoe Falls. Two 55 kW rotary balancer sets are used to give a three-wire system with 125 V between each outer and the centre wire of the three-core, 1,500 A cable which connects the power station with the floodlights.

CHOICE OF LIGHT SOURCE.

A survey of light sources to find a high-brightness lamp with a spectral energy distribution suitable for the effective use of colour filters led to the choice of the well-established high-intensity carbon arc lamp. In such a lamp the light source is substantially a ball of luminous vapour from the cerium fluoride core of the positive carbon. The luminance is more than three times that of a low-intensity arc and this increase in luminance is very desirable for long-range narrow-angle projection. It permits high beam intensity with a relatively small diameter optic, an important consideration in view of the restricted space available for the floodlights. The colour is blue-white, and the spectral energy distribution enables rich colours to be obtained with appropriate colour filters. Because of the high effective colour temperature, there is an adequate proportion of blue light.

To use all the available power, while providing sufficient projectors to give a varied colour pattern on the Falls, a lamp rating of 75 V, 150 A, was chosen, which allowed 20 projectors to be installed. At this rating the burning rate of the positive carbon is some $9\frac{1}{4}$ in. per hour, which made it impracticable to accommodate a carbon able to burn for the whole of one performance in a barrel of acceptable length. A semi-automatic lamp in which the positive carbon has to be changed once nightly was therefore adopted. The design chosen was the lamp developed by Savage & Parsons Limited, features of which are a narrow,

hollow lamp column giving a minimum of obstruction, efficient cooling of positive brushes, ease of positive carbon replacement and maintenance and neat design of the positive head.

Views of the projectors are shown in fig. 2 and 3. The units are of compact design, the overall length being only 6 ft., the width 4 ft. and the height about 9½ ft. Originally a simple symmetric optical system was to have been used, but after tests in England in which water from fire hoses and smoke bombs were used to give the effect of the Falls and their spray, two front glasses were selected which enabled any unit to give a number of different beams, all of which were used in the final lighting plan.*

Fig. 3.—The Canadian Falls seen from the rotunda.

PROJECTOR CONSTRUCTION.

The floodlight barrel contains the arc lamp and mirror, with the carbon " feed-up " mechanism housed in a separate box recessed into the side. To permit the positive carbons to be inserted in the restricted barrel length, the lamp is racked 5 in. towards the mirror, and limit stops ensure correct re-positioning after re-carboning. A " Focuscope " (which shows visually whether the carbons are correctly positioned), carbon-replacement warning light, extractor fan, access doors for servicing and the re-carboning light inside the barrel follow conventional searchlight practice. An isolating switch is provided on the barrel.

Attached to the front of each projector is an anodised sheet aluminium housing, 8 ft. high by 4 ft. wide by 2 ft. deep. Framed in the front and rear faces are two 38 in. square, ⅜ in. thick, toughened glasses which allow the floodlight beam to pass straight through the unit and one or other of the special front glasses mentioned above is mounted inside this clear front glazing. The unit contains five vertical channels on each side which allow five colour frames, each 37 in. square, to pass up and down. Each frame houses a sheet of " Cinemoid." The sides of the channels are removable by quick release studs to allow the colour frames to be serviced easily. Each colour frame is operated by an individual driving motor of the capacitor induction type, the coils being former wound and impregnated to withstand humid conditions.

The five specially chosen filters in each colour control unit may be used singly or in combinations of two or three, and permit 15 hues to be projected.

The colour for each projector is selected by an operator seated in view of the Falls at a remote console which is arranged so that it can be operated from a sitting position while viewing the effect. A panel inclined at 45 deg. carries 20 vertical banks of switches with an indicator showing the colour controlled by each row. Each bank of switches comprises five two-way and off toggles, so that all five switches for each individual colour controller are sited one below the other. The over-riding master switch operating through 20 relays not only enables each colour sequence to be preset and brought into effect by the operation of the master controller, but also permits an instant return to overall white lighting whatever the positions of the individual controls.

INSTALLATION CONDITIONS.

In addition to rust and corrosion, the problems of condensation, extremes of temperature and icing-up of access doors, hinges and catches had to be considered. Throughout the design and construction care has been taken to guard against the effects of these unusual weather conditions and to ensure long life and reliability of the equipment.

**Engineering*, Vol. 185, p. 230, Feb. 21, 1958.

History of the Tungsten Filament Lamp

By J. A. MOORE, B.Sc.,
Research Laboratories.

AFTER World War II it was thought by many that the tungsten filament lamp would be superseded by the hot cathode fluorescent tube, having four or five times the efficiency and at least five times the life. In fact, this has not occurred, and considerations of compactness, ease of handling, simplicity of operation and low lamp price for the tungsten lamp evidently have outweighed to some extent the merits of high efficiency, low surface brightness, choice of colour and long life, obtainable with the fluorescent tube.

Indeed, the number of tungsten filament lamps in use has increased considerably and home sales of General Lighting Service (G.L.S.) lamps alone have risen by at least 25 per cent over the last five years. The 100 W filament lamp now has the largest percentage of total annual sales, this having increased from 20 per cent in 1939 to 30 per cent at the present time. In the same period, 150 W lamp sales have increased very considerably from 3 per cent to 11 per cent, while 40 W sales have dropped from 22 per cent to 13 per cent of the total (fig. 1). The increase in sales is partly due to a more imaginative approach to lighting design by lighting engineers and architects, and partly to a growing appreciation of the value of good lighting on the part of the users. In addition, there is a rapidly mounting demand for tungsten projector lamps used in colour transparency projectors and for very high wattage lamps in film and television studios, where the broad spectral band of incandescent radiation is essential for colour work.

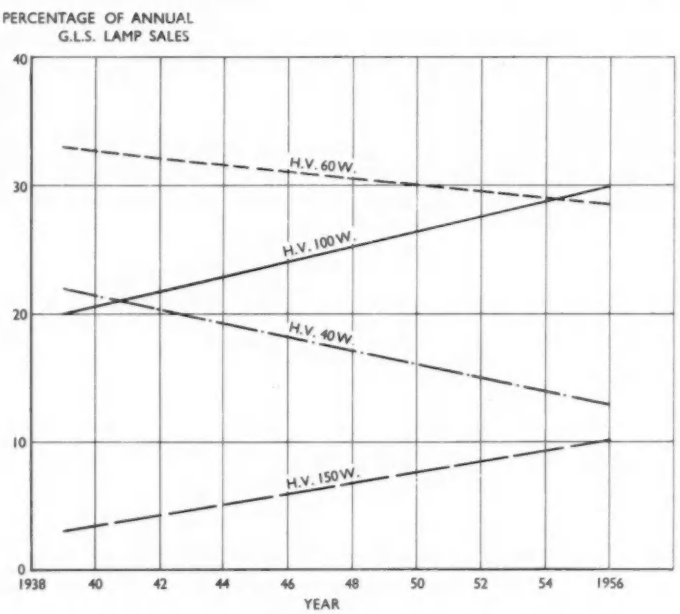


Fig. 1.—The increasing demand for lamps of the higher wattage ratings.

These facts underline the continued importance of the tungsten filament lamp in the lamp industry, and this article traces its development from the beginning of the century, with particular reference to the G.L.S. lamp. The tungsten lamp " family tree " has grown rapidly until there are now some 2,000 types, ranging from the surgeon's tiny " grain of wheat " lamp to the 20 kW studio lamp. These will not all be discussed here, although, of course, the same problems of development have applied in all types to a greater or lesser degree.

The gas-filled tungsten lamp has a history dating back to 1913. Since then there has been a continuous effort to improve its performance and uniformity year by year. For a product already developed to a high level of quality as the result of forty years' work, substantial improvements are not easily achieved today. The dynamic nature of the industry and its achievements are due in a large measure to a seemingly parodoxical coupling of keen competition between lamp manufacturers on the one hand, and a close liaison in technical matters and interchange of manufacturing information on the other.

The following quotation from the findings of the Monopolies and Restrictive Practices Commission's report on the Supply of Electric Lamps, published in 1951, is not without interest:

> "A rapid and comprehensive exchange of information about new developments, as they occur, has encouraged the more rapid application of new discoveries and must also, we believe, make more effective the efforts of individual research departments. Although we have recorded our opinion that prices were unduly high before the war, none the less it is only fair to record also that much of the benefit of this technical progress has been passed on to the public in a progressive and substantial reduction in the prices of lamps; in the case of general service filament lamps this trend has continued even during the last twelve years when prices of most other goods have been rising. . ."

Apart from independent bi-lateral agreements, two main factors have been largely responsible for raising the quality standards of tungsten filament lamps, namely the British Standards Institution and the pre-war "Phoebus" Agreement between leading lamp manufacturers. The first British Standard Specification for Tungsten Lamps, No. 133, was published in June, 1921, and stipulated an average life for a sample of 10 lamps of not less than 1,000 hours, which requirement demanded an objective average life appreciably higher than 1,000 hours. This specification also laid down limits on other lamp parameters, including efficiency. The British Specification has since that time been frequently revised, specifying ever higher averages and closer limits and thus ensuring the best possible product. The latest revision, B.S.161, was published in April, 1956.

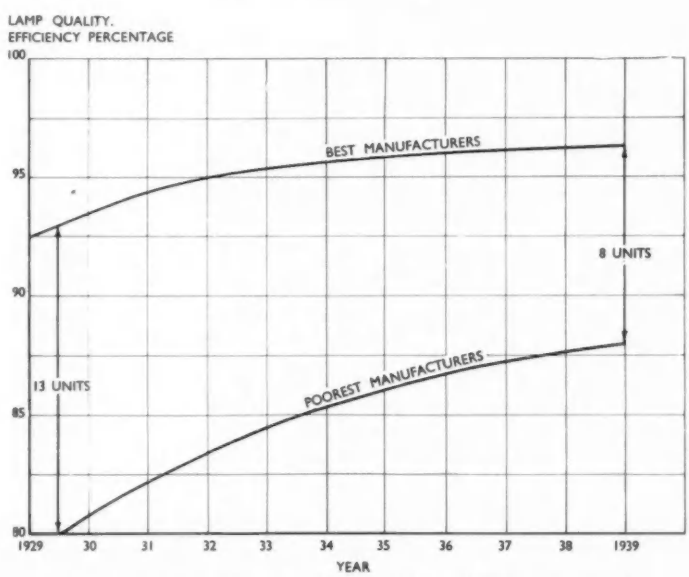


Fig. 2.—Improvement of lamp quality and uniformity in the pre-war decade.

The "Phoebus" Agreement was drawn up in 1924 by 39 of the leading lamp manufacturers of the world. Article 2 of the Agreement stated: "The purpose and intent of this Agreement is to secure the co-operation of all parties in securing and maintaining a uniformly high quality of product and promoting more efficient methods of electric illumination and the increased use of light to the advantage of the consumer." The Phoebus Laboratory, at its headquarters in Geneva, carried out photometry and life tests on lamps sent annually by its members, and issued yearly reports to all members giving all the results. This gave the first opportunity to lamp manufacturers to compare their products with a definite standard of comparison and with each other. Lamp quality was expressed in a single figure called the "Efficiency Percentage" and was based on a Phoebus Standard Comparison Efficiency for all vacuum and gas-filled tungsten lamps. The "Efficiency Percentage" is defined as the average lamp efficiency throughout life corrected to a life of 1,000 hours, and expressed as a percentage of the Phoebus Standard Comparison Efficiency. This figure is still used today by the life test departments of the large manufacturers, although it is not used for the purposes of the British Standard Specification. This annual international comparison system gave a considerable impetus to the improvement of lamp quality and uniformity. By 1939, when the Phoebus Agreement was terminated by the outbreak of war, the quality difference between the worst and best manufacturer had almost halved itself in 10 years (fig. 2).

The incandescent filament lamp may be said to have been the forerunner of the scientific revolution which has taken place in the last fifty years. The discovery of electron emission from heated tungsten and carbon filaments and the work of Edison, Fleming, J. J. Thomson and Richardson arose from work associated with the development of incandescent vacuum electric lamps at the turn of the century. This led to the radio valve and the birth of the radio and electronics industry. Since the lamp industry was established by the time the radio valve was developed, there was much valuable experience available in component manufacture, pinch making, assembly and pumping which enabled the valve industry to develop very rapidly. In fact, the radio valves used by the British forces during the first world war were produced in the factories of the large lamp manufacturers. The electrical supply industry also owes much of its early growth to the great demand for the electric carbon and tungsten lamps at the beginning of the century.

THE TUNGSTEN LAMP UP TO 1930.

To summarise the early history of the electric filament lamp it is necessary to go as far back as 1840. At that time W. R. Grove, the British inventor of the cell named after him, was experimenting in his laboratory with a coiled platinum wire heated to incandescence in nitrogen and other gases by an electric current. Grove discovered the advantages of coiling to reduce heat loss and to improve luminous efficiency. He also discovered that nitrogen was the best gas to use since it had the least heat conductivity. Over 50 years later Langmuir continued this work in a comprehensive manner, which resulted in the commercial introduction of the gas-filled lamp.

In 1878 Swan exhibited electric lamps with carbon-rod filaments and a year later Edison made the first practical electric lamp consisting of an evacuated bulb with carbonised cotton thread as filament. Various methods of producing carbon filaments were then developed (fig. 3), and it was not until 1898 that the first metal filament was introduced. This was the osmium filament of Dr. Welsbach of Germany. The General Electric Co. Ltd. acquired the rights of this and other German lamp inventions and established the electric metal filament lamp market in this country.

After the osmium filament came the metallised carbon filament marketed in 1905, and the tantalum filament in 1906. Tungsten, because of its high melting point (3,655 deg. K.), low evaporation rate at high temperatures, and other characteristics, had long been recognised as a suitable material for lamp filaments. Its commercial use was delayed for several years because of the enormous metallurgical problems involved in producing the long fine wire required for lamp filaments. Squirted tungsten filaments had been introduced in 1904 and in 1906 Dr. Coolidge of the United States produced the first drawn tungsten wire, which is the basis of the modern tungsten lamp. The Coolidge patent was the first to describe the production of ductile tungsten. This was achieved by the novel technique of reduction of the tungsten oxide to a fine metal powder, followed by compression into bars, sintering, swaging and wire drawing. These techniques formed the basis of the modern industry of powder metallurgy.

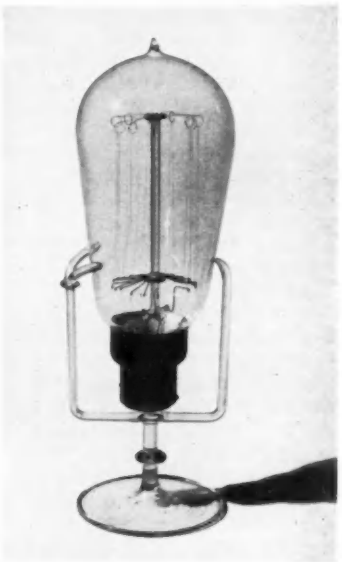


Fig. 4.—An early vacuum tungsten lamp using ten separate hair-pin filament loops.

Fig. 3.—An early type of twin-filament carbon lamp (1903).

Such an advance was a major achievement, since it led to the production of a stronger wire which could be handled more readily and made possible the shaping of the wire into coils of very small diameter. All previous tungsten filaments had proved to be far too fragile and brittle to wind into coils.

By 1909 the G.E.C. had started its own Osram lamp production at Hammersmith. The name " Osram " is derived from the metals osmium and wolfram (tungsten), which at that time were the filament materials used in the lamps sold by the Company.

Filaments were made of long straight wires mounted under tension in the form of a cage and enclosed in an evacuated bulb (fig. 4). The operating temperature of the filament was limited by the high evaporation rate and the eventual filament rupture due to the mounting tension.

Because of its higher melting point tungsten soon replaced osmium as a filament material. About this time Langmuir in the United States began his study of the effects on lamp efficiency and filament evaporation of coiling and gas filling, and in 1913 he patented the gas-filled lamp containing a coiled filament, upon which is based the tungsten lamp of today.

Langmuir found that the lighted filament of a gas-filled lamp is surrounded by a cylindrical layer of relatively stationary gas in fairly close proximity to the filament. A rapid convection stream occurs beyond this at some distance from the filament. The diameter

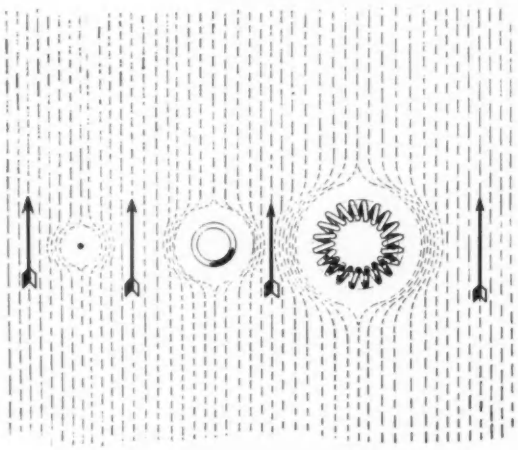


Fig. 5.—Flow of gas around straight and coiled filaments.

of this " Langmuir Layer " was found to be largely independent of the diameter of the incandescent cylinder so that by coiling the filament into the equivalent of a much larger diameter cylinder the length of the gas layer was greatly reduced, but its diameter hardly affected (fig. 5). Since heat losses and filament evaporation were found to be dependent on the dimensions of the layer, coiling the filament reduced the heat loss and hence raised the luminous efficiency of the lamp. The gas-filling helped to suppress evaporation of the hot filament and enabled the operating temperature to be increased without decreasing the life, thus contributing further to the increase in efficiency. Langmuir showed that other factors affecting the heat loss and evaporation were the molecular weight of the gas and its pressure in the lamp.

Coiling the filament introduced considerable problems, since the coil form was unstable, resulting in sagging and opening of the pitch of the coil. The catenary shape assumed by the filament (fig. 6) increased the heat loss and reduced the efficiency of the lamp. Another Coolidge patent of 1910 claimed the introduction of thoria as an additive during tungsten wire manufacture. This improved the

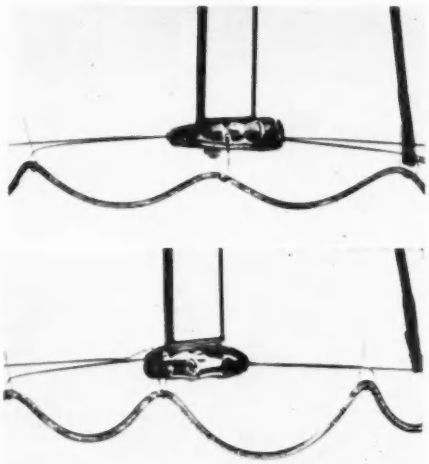


Fig. 6.—Comparison of sag in two single-coil filaments after 1,000 hours' burning.

ductility of the wire by creating a fine crystal structure which prevented brittle filament breaks at the grain boundaries. This " off-setting " is due to adjacent crystals slipping across one another on the face where they meet (fig. 7). Since this event can occur only where the crystal boundaries extend across the diameter of the wire, a finer crystal structure makes this possibility less likely. However, the addition of thoria did nothing to reduce the tendency of the filament to sag.

Up to about 1924 it appeared that the problem of sagging was incapable of solution in spite of intensive efforts by all the lamp manufacturers to overcome the defect. The solution of this problem was made more desirable by the discovery that even in vacuum

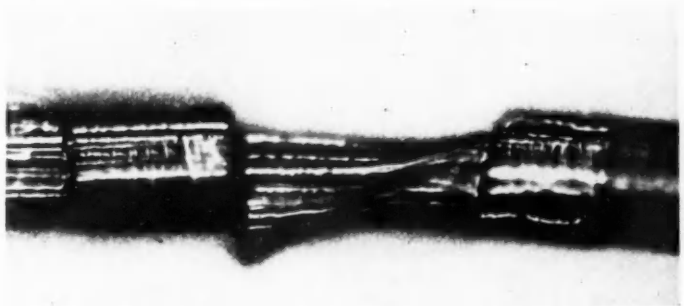


Fig. 7.—Filament showing " off-set " at a crystal boundary, resulting in a brittle wire (x100).

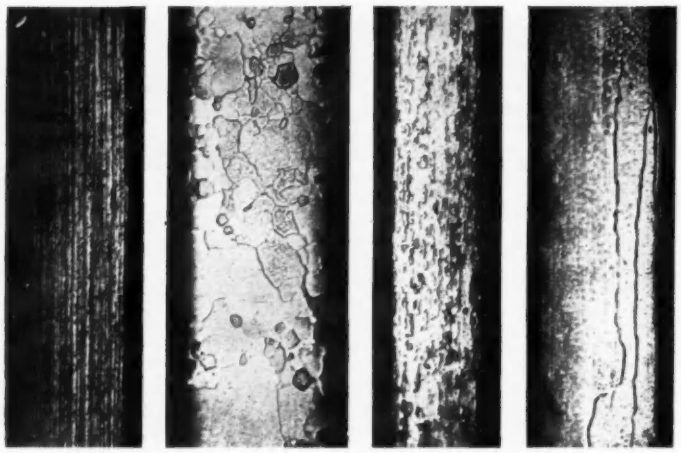


Fig. 8.—Microstructure of tungsten wire (x150).

(a) *As drawn. Before recrystallisation.*
(b) *Recrystallised commercially pure tungsten (0·05 per cent impurities). Large crystal structure with no orientation of growth.*
(c) *Recrystallised thoriated tungsten (0·70 per cent thoria). Fine crystal structure.*
(d) *Recrystallised alumina "non-sag" tungsten. Large overlapping crystal structure showing long crystal boundaries parallel to wire axis.*

lamps, coiling of the filament leads to greater efficiencies for the same lamp life when compared to the straight wire filament, because the rate of evaporation is much reduced due to tungsten condensation within the coil. This enables the operating temperature to be raised, giving a higher efficiency, which more than compensates for the poorer radiation characteristics of a coil compared with a straight filament at the same temperature. The resulting net gain thus arising from coiling is well worth while, with the added advantage of a more compact source.

Although Langmuir in 1914 had suggested coiled-coil filaments in gas-filled lamps to reduce further the cooling loss, the instability problem prevented their realisation. Eventually, a solution was found by the addition of traces of silica, alumina and alkali oxides to the tungsten, combined with improved control of all the manufacturing processes (fig. 8). Problems of coil stability and uniformity of behaviour, however, remain today and are receiving continual attention.

The decade 1920-30 was noteworthy for the rapid development of manufacturing techniques by which high speed automatic machines replaced hand work and hand-controlled machine processes, and also for a revolutionary change in the concept of the function of inspection.

The main factor governing the introduction of automatic processes was the uniformity of the lamp components, particularly the glass components, such as the flange tube and the lamp bulb. With non-uniform parts each lamp needed individual treatment by hand. There was much progress made on the control of glass composition which enabled even fluidity and stability to be maintained. High electrical resistance at elevated temperatures was also necessary. These requirements were met in glasses of low cost and automatic machines followed.

Up to 1920 the function of inspection was to reject any undesirable product. The growing use of pictorial methods, based on formal statistics, for the presentation of data led to inspection being concentrated on the manufacturing process, particularly on those stages of manufacture which had the greatest bearing on the quality and uniformity of the finished article. This new concept of quality control using statistical methods was pioneered largely by the G.E.C. for lamp production, and in particular by Dr. Dudding of the Research Laboratories.* The Company's advice is still eagerly sought by diverse industries introducing statistical quality control methods.

By 1930 the basic technical problems associated with the gas-filled tungsten filament lamp, its automatic production, and its close manufacturing control, were well established.

THE MODERN TUNGSTEN LAMP.

1. The Filament.

Single coil tungsten filaments are now used for the whole range of general service vacuum and gas-filled lamps from 15 watts to 1,500 watts. They are made of tungsten containing traces of silica or alumina additives,

* *G.E.C. Journal*, Vol. 22, pp. 161-165, July, 1955.

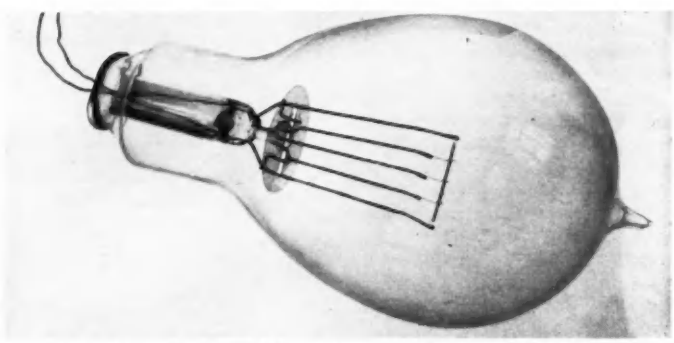


Fig. 9.—An early coiled-coil filament lamp made at the G.E.C. Research Laboratories in 1924.

usually termed " dopes," which render the tungsten coils relatively stable.

Coiled-coil filaments were produced in the Research Laboratories of the Company in 1924 (fig. 9), but it was not until 1934 that high voltage general service coiled-coil lamps were first marketed.

TABLE 1.

Fundamental Developments in Filament Lamps from 1841 to 1934

1841	Coiled platinum filament in gas	Grove
1879	Carbon filament lamp	Swan and Edison
1880	First commercial lamp	Edison
1898	Osmium filament (first commercial metal filament lamp)	Welsbach
1904	Squirted tungsten filament	Just and Hanaman
1906	First drawn tungsten wire	Coolidge
1907	Pressed tungsten filament	Various
1913	Gas-filled coiled filament lamps	Langmuir
1924	" Non-sag " silicated wire	Various lamp manufacturers
1934	Coiled-coil lamps marketed	Various lamp manufacturers

The delay was in part due to the development period required to design a successful automatic mounting machine to handle the delicate coiled-coil filaments without undue breakage during mounting. The problem of arcing or " flashing " within the lamp across the shorter coiled-coil was an additional delaying factor.

The coiled-coil filament is now far more stable than it was twenty years ago, but further improvement is desirable. Wire preparation, coil treatment, mounting, lamp assembly, processing, and initial lighting are being studied for their relative effects on sag, both that which occurs in the first fractions of a second in which the lamp is lit, and that which occurs progressively during lamp life.

2. THE GAS FILLING.

The requirements for the filling in gas-filled lamps are :

(1) It must be chemically stable and not react with the lamp components at high temperatures.
(2) Its heat conductivity must be low.
(3) It must suppress evaporation efficiently.
(4) It must be available economically in large quantities.
(5) Its ionisation potential must be high, to prevent " flashing."

Nitrogen was the only gas which came anywhere near to meeting these requirements until argon became commercially available. Langmuir's work showed that argon was far superior to nitrogen as a " lamp gas ", mainly due to its higher molecular weight and lower heat conductivity. It was also totally inert, whereas nitrogen slowly reacts with hot tungsten, causing blackening of the bulb. However, it was found that argon could not be used by itself in high voltage coiled filament lamps because of its low ionisation potential, which led to serious " flashing ", particularly at switching-on. This flashing often destroyed the lamp because of the high current passed by the arc. Nitrogen mixed with the argon inhibited flashing and its use for this purpose became universal.

The present filling gas in general service lamps consists of 93 per cent argon and 7 per cent nitrogen at a pressure of about 700 mm. Hg. measured with the lamp cold. This gas composition and pressure has been reached following much experiment and development since the first world war.

The first lamps were filled to limited gas pressures to reduce the heat loss which became serious due to sagging of the single coil filaments and the progressive opening of the pitch of the coil as the lamp was burned. The nitrogen content of these early lamps was as high as 20 per cent to suppress the high tendency to " flash " at the reduced filling pressures.

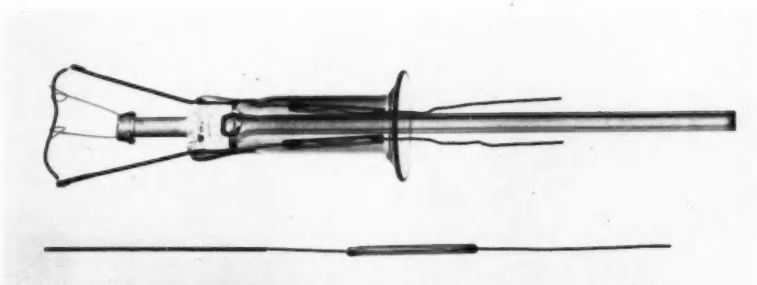


Fig. 10.—Top: Modern Osram G.L.S. lamp filament mount. Bottom: Lead wire showing glass-sheathed fuse and 4-part construction.

As the coiled filaments became more stable it was realised that the reduced evaporation which occurred at higher pressures outweighed the increases in heat loss and made possible higher efficiencies for the same life. The higher filling pressure reduced the tendency to flash, which allowed a decrease in the nitrogen percentage. The trends towards higher gas pressures continue and may make it possible to reduce again the nitrogen concentration, with further gains in efficiency.

Krypton or xenon would be more advantageous than argon as a filling gas since they are heavier and poorer heat conductors. These gases were first separated commercially in 1935, some 20 years after the commercial extraction of argon, but they are still too expensive to use on a large scale in general service lamps. Krypton is used, however, in the miners' cap lamp, where high brightness and good efficiency are of the first importance.

General service gas-filled lamps using coiled-coil filaments are made in wattage ratings from 40 W to

100 W. The efficiencies are some 20 per cent higher than corresponding single coil lamps due to the reduced energy losses by conduction and convection in the gas filling. Because of the very fine wire used in wattage ratings below 40 W, the cooling effects of the gas filling outweigh its advantages and these lamps are not gas-filled.

3. Lamp Fuses.

At the moment of switching on a gas-filled lamp, there is a tendency for an arc to occur between the filament support leads, or, if the filament is defective, at a break in the coil. Unless suitable precautions are taken, this could lead to blown fuses or possibly even to a burst lamp if the mains fuses are unusually heavy. This phenomenon is known as " flashing." To avoid the inconvenience associated with blown fuses, the modern Osram lamp contains sealed glass-sheathed fuses in both leads fitted within the cap, which afford complete protection to the user (fig. 10).

As mentioned earlier, the problem of flashing accompanied the introduction of gas-filling. Apart from the effects of the nature of the gas and its pressure, much work was done about 25 years ago on the influence of lamp design and other aspects of lamp manufacture on the flashing problem. In 1930 20 per cent or more of single coil lamps flashed either prematurely or at the end of life, but due partly to greater control during processing as automatic manufacture grew, this figure was reduced to about 5 per cent in 1939 and is now less than 1 per cent.

Lamp fuses were first introduced in 1934 with the coiled-coil lamp. These were essential since almost 100 per cent of coiled-coil lamps flash at the end of life. The first fuses were unsheathed, but were unsatisfactory because of their failure by oxidation and chemical attack from the capping material and soldering fluxes. Extensive trials involving many thousands of lamps were carried out on fuse materials, dimensions and stability resulting in the glass-sheathed fuse. Although they were expensive, sheathed fuses were immediately used in coiled-coil lamps just before the war and are now also used in all Osram single-coil gas-filled lamps.

4. Precision in Lamp Processing.

From what has been said it may be realised that the tungsten lamp is a most sensitive and intricate device calling for extreme precision and cleanliness in all stages of manufacture. The tungstic oxide prepared from the ore has to be of the highest purity, with a specific particle size distribution. The oxide preparation and the reduction process to the metal powder have a large bearing on whether or not the filaments made from it will reach the standards demanded in modern lamps.

The wires most commonly used in lamps for general lighting service vary in diameter from 0·015 mm. for the H.V. 15 W lamp to 0·05 mm (fig. 11). These wires must be accurately round with local variations in diameter not greater than 1 per cent, i.e. less than 15 millionths of a centimetre. Extreme accuracy must therefore be maintained in the diamond dies used to draw the wire. Filament size is usually controlled by weighing fixed lengths of wire, cut in special gauges, on a high precision torsion balance.

The wire is wound in the form of a fine helix about a core or mandrel of about 3 to 6 times the wire

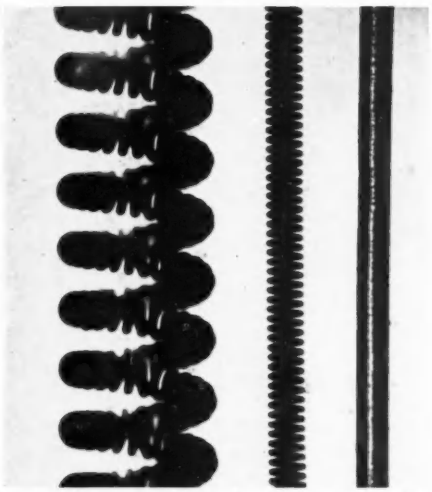


Fig. 11.—H.V. 40 W coiled-coil and H.V. 15 W single-coil filaments compared to a human hair (x100).

diameter. The tolerances for mandrel diameter are smaller even than for the wire, and the hardness of the mandrel metal must be constant so that the degree of " biting in " of the wire as it is wound does not vary. The speed and tension of coiling are very accurately controlled, so that the total length of wire in every cut coil falls within very small limits. Tolerances on

Fig. 12.—Sag and pitch distortion produced by deliberate contamination of filament surface.

wire and mandrel diameter are matched to reduce the overall tolerance on the finished filament coil. The distance between turns of the coil is about 0·2 to 0·6 times the filament diameter and must not vary by more than a very small percentage. To prepare a coiled-coil filament the primary coil, while still on its mandrel, is coiled accurately a second time. The primary and secondary mandrels are eventually dissolved out by acid treatment. The length of wire in a coiled-coil filament is about 100 cm., while the coil length is only 3 cm.

Such a fine wire is extremely sensitive to contaminants (fig. 12), particularly because of the cyclic chemical reactions which can occur over the very broad temperature range within a lamp, from about 50 deg. C. at the coolest part to about 2,500 deg. C. at the filament. Less than ten parts per million of water vapour will cause an increase in filament sag and possible early failure due to filament oxidation (fig. 13). A similar quantity of hydrocarbon vapour will cause the filament to squirm and become distorted (fig. 14).

To render the lamp less sensitive to slight variations in pumping quality and assembly conditions, phosphorus getter is used to react initially with any contaminants present. The filament is dipped into a rotating pot containing phosphorus suspended in alcohol, before it is sealed into the lamp bulb. The amount and quality of the getter itself is very critical.

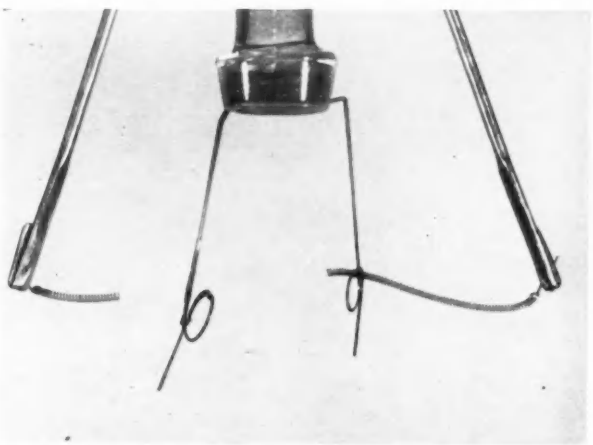


Fig. 13.—Artificially produced filament failure due to water vapour attack. Oxide deposit on support wire.

5. Lamp Design.

To design a tungsten lamp of given voltage and wattage to give the maximum possible efficiency for a given life is complicated, and does not easily lend itself to a solution on a theoretical basis. Almost all the parameters of lamp design (wire size, wire length, coil diameter, coil pitch, coil length, coil shape, nitrogen content of the gas, filling pressure, bulb volume, size and shape) are inter-dependent and each affects the initial efficiency, efficiency maintenance and life of the lamp to a greater or lesser degree.

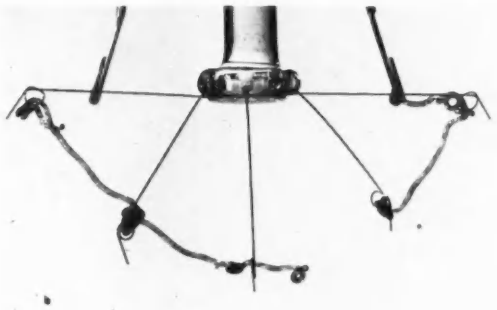


Fig. 14.—Artificially produced filament "squirming" due to oil vapour.

There are, however, empirical design methods for the filament which have been developed over the years, with limits on the coil diameter and pitch to maintain coil stability and including compensation procedures for the manufacturing tolerances. Theoretical work was carried out before the war on the inherent luminous efficiency of an incandescent tungsten coil and its dependence on coil pitch and diameter, but this has not been related yet to the effects of filament sagging and heat loss, and hence to the lamp efficiency in lumens per watt of a practical gas-filled lamp.

Unlike that of the fluorescent tube, the life of a tungsten lamp is largely determined by its initial efficiency. Throughout the last thirty years, the designed minimum average life of general service lamps has remained at about 1,000 hours and recent investigations have shown this value still to be the most advantageous to the user.

The internally frosted or pearl bulb was introduced in 1925 to diffuse the light from the bright filament. There is negligible light absorption in the diffusing bulb, the smooth outer surface of which does not readily collect dirt and is in any event easily cleaned. Due to the demand for high wattage lamps in open domestic lighting fittings, the silica coated or Silverlight lamp was marketed in 1950. This has a pleasant white appearance of relatively low surface brightness, but the internal coating absorbs six to eight per cent of the light output.

The Pink Pearl lamp was marketed in this country in 1956. It is coated internally with a pink suspension, or alternatively has a smooth pink ceramic coating on the external surface of the bulb. The soft pink tinted light is very pleasant for domestic and social lighting.

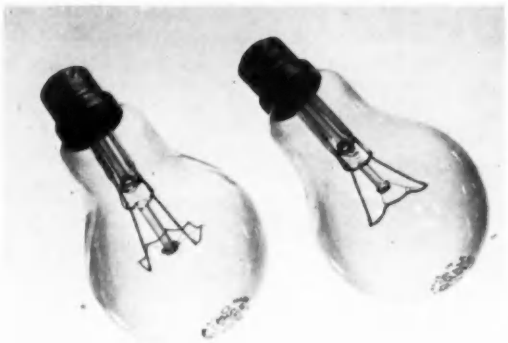


Fig. 15.—Modern clear Osram H.V. 100 W single-coil and coiled-coil General Lighting Service lamps.

Since the pink colour has been achieved by a subtractive process there is inevitably some loss in efficiency.

Continuous improvements are being made in the stability of the lamp filaments, and lamp design has been modified to exploit these improvements to the fullest extent to achieve the maximum increase in lamp quality (fig. 15). The order of filament stability now possible has enabled two such design modifications to be made within the last three years :

(1) In Osram high voltage coiled-coil lamps the number of supports used to carry the filament between the lead-wires has been reduced from three to two (fig. 16). Since the filament coil length remains unaltered, there is an increase in filament weight between points of suspension of about 9 per cent, which calls for a high degree of coil stability. The reduction in the number of supports means that fewer cold points are introduced along the coil length, and worthwhile quality improvements have been gained.

(2) In the U.S.A. an improvement in quality has recently been obtained by mounting the filament vertically in the bulb. This localises the evaporated tungsten to a small area of the bulb above the filament axis, resulting in a better efficiency maintenance throughout life, and a slightly longer life for the same efficiency if the lamp is burnt vertically with the cap uppermost. The single coil filament hitherto widely used in the States has at the same time been replaced by a double coil giving a further gain in efficiency.

Axial mounting of the filament is difficult to apply in this country in ratings below about 200 W since the usual supply voltage is double that in the U.S.A., and necessitates the use of fine filaments which cannot be mounted vertically with a high degree of stability. There is little doubt that the horizontal arrangement of the filament so widely used in this country possesses special advantages in obtaining the best light distribution in the working plane.

6. Lamp Performance.

Improvement in filament lamp quality is not so much the result of spectacular new developments as of continual attention to detail and the introduction of such small design modifications as those described above.

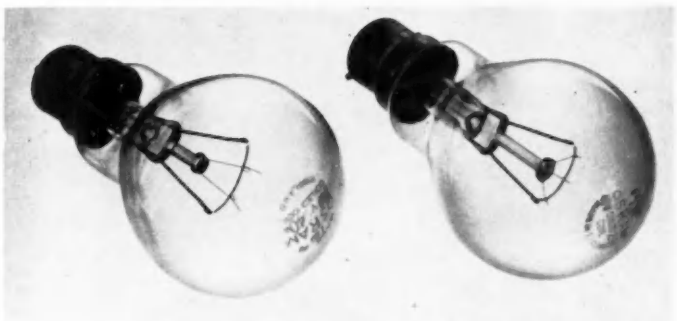


Fig. 16.—The 2-support filament suspension for coiled-coil lamps compared with the old 3-support design.

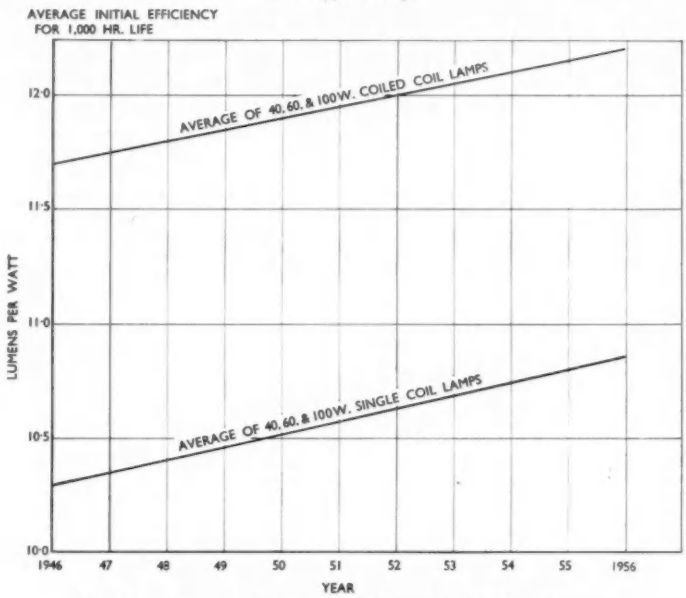


Fig. 17.—Improvement in Osram G.L.S. lamp quality since the war.

As mentioned earlier, the quality of the lamp can be expressed in a single figure called the " Efficiency Percentage ", which depends on the initial filament wattage, the initial efficiency in lumens per watt, the lamp life and the efficiency maintenance during life. Since the war there has been a general quality increase of about 6 per cent (5 units in Efficiency Percentage) for both single-coil and coiled-coil lamps (fig. 17).

Apart from the rises in average level of lamp quality in terms of lamp efficiency and maintenance, increasing importance is being given to the concept of uniformity of performance between lamps. Statistical analyses of data show the magnitude of variability and how it is distributed within and between lamp batches on different occasions, and these analyses are essential in assisting the intensive programme now in hand in all aspects of lamp making to improve the already high level of uniformity. The task is complicated and intricate due to the considerable inter-dependence of lamp parameters.

7. The Manufacturing Process.

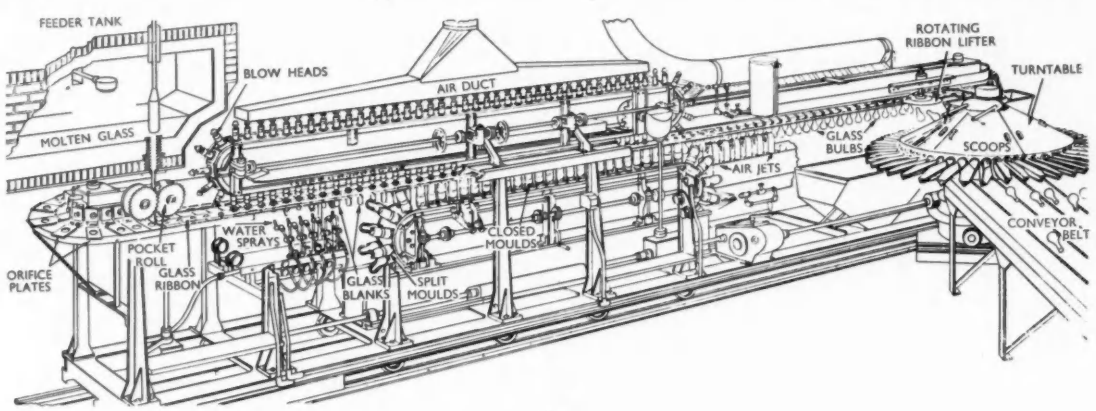
To deal adequately with the manufacturing process of modern Osram tungsten lamps is virtually impossible within the compass of the present article. Four distinct industries are involved, viz. the manufacture of glass and glass components, the manufacture of metal wires, the extraction of rare gas from the atmosphere, and the assembly of components produced by the above industries into the finished tungsten lamp. In this review the main features in each of these component industries and the sequence of manufacturing operations in lamp assembly are briefly described.

7(*i*) *Glass Components.*

The physical and chemical characteristics of the glass are carefully controlled so as to ensure uniformity of behaviour of the glass during component manufacture and assembly.

The glass components are the bulb, flanged tube, exhaust stem and solid rod to hold the filament supports. Lamp bulbs are manufactured at Harworth, near Doncaster. The factory is built around two machines,

(*a*)



(*b*)

Fig. 18.—Past and present methods of lamp bulb production.

(a) Blowing lamp bulbs by hand in 1910.

(b) Diagram of the ribbon bulb making machine at Harworth, producing 12 bulbs every second.

which can turn out a million and a half lamp bulbs per day. This is more than enough to cater for all the British requirements. The earlier Westlake and Ohio bulb blowing machines by comparison produced seventy-two thousand and one hundred and fifty-six thousand bulbs per day respectively. Fig. 18(a) shows the blowing of lamps by hand before the foregoing machines were introduced.

The operation of the machine is entirely automatic and involves a continuous ribbon of molten glass fed from a large tank. This ribbon is carried on a moving belt and blow heads are lowered on to it. These heads blow out " bubbles " in the ribbon which are then enclosed by split moulds having the shape of the lamp bulb (fig. 18(b)). Each bubble is blown out against a cushion of steam on to the mould, which is rapidly rotated. The cushion of steam is important in that it produces a perfectly smooth surface on the bulb. The bulbs are then cut from the ribbon by a rotating disc called a " ribbon lifter," and allowed to fall on to a conical turntable which delivers them to a conveyor belt.

The flanged tube component of the lamp mount which carries the filament is manufactured within very small tolerances from lengths of glass tubing. The tubing has to be of high quality with uniform diameter and wall thickness to avoid cracking during and after sealing-in operations. The same care is taken over the dimensional uniformity of the stem tubing and rod, and continual checks are made of roundness and evenness. At the Glass Works every piece of tube and rod is gauged into classes within narrow limits to ensure satisfactory operation of the automatic machines used in lamp assembly.

7(*ii*) *Metal Wire Components.*

Apart from the filament itself there are two other wire components within the lamp, namely the molybdenum wires which support the filament, and the lead-in wires which connect the cap contacts to the filament. The lead-in wires themselves have four parts, namely, a copper outer lead, a constantan fuse wire, a copper-clad nickel-iron alloy sealed into the glass mount and a nickel inner lead to which the filament is attached (fig. 10). The materials for these wires must conform to certain specifications and the batches of wire are carefully chosen for their use in lamps. The molybdenum support wires particularly are produced in similar fashion to the tungsten filament wires and with close control. These supports need to be sufficiently strong and ductile to withstand the rough handling to which lamps are sometimes subjected.

For the copper-clad wire, copper is electro-plated on to a nickel-iron core which is then reduced by a series of wire drawing operations such that the copper layer is extremely thin. The development of this wire was the result of much experiment in matching the coefficients of expansion of the wire and the glass into which it is sealed. Very early lamps involved the use of costly platinum to achieve air-tight glass-to-metal seals.

7(*iii*) *The Filament.*

The tungsten ore is decomposed by acid treatment to tungstic acid, which is purified by repeatedly dissolving in ammonia and re-crystallising to ammonium paratungstate. After treatment with caustic potash and precipitation, pure tungstic oxide is produced. This flows as a yellow suspension into washing tanks, after which it is dried. This is done in three stages—centrifuging, steam drying, and ignition in electric furnaces. The oxide is next ground to a particular particle size distribution. Before reduction to tungsten powder, which is carried out in a stream of hydrogen at about 1,000 deg. C., very small quantities of thorium, silicon or aluminium compounds are added. These assist in removing the last traces of impurity during the reduction process and play a fundamental part in determining the crystal size and growth behaviour in the final filament.

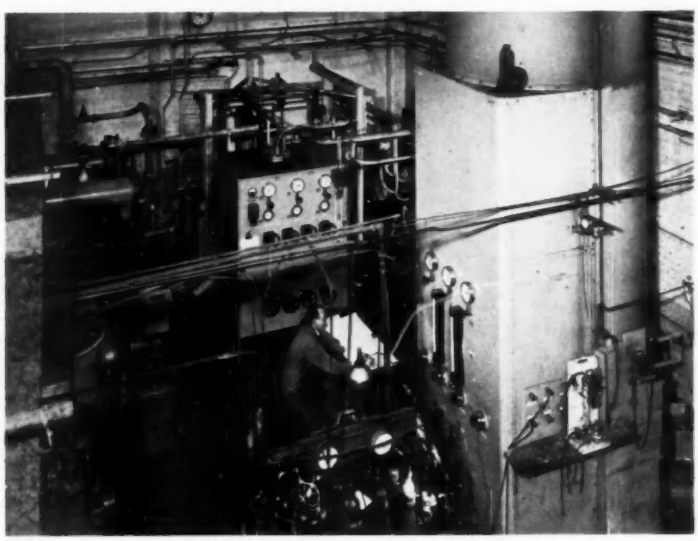


Fig. 19.—Argon gas plant at Hammersmith.

The metal powder is pressed into bars about 8 in. long and $\frac{1}{4}$ in. square by a 200 ton hydraulic press. Each bar is at this stage extremely fragile. It is now sintered to a temperature not far below the melting-point in a hydrogen atmosphere by passing through it a current of about 3,000 amp. The bar is next swaged by

passing, while heated to about 1,000 deg. C., through pairs of hammers, which strike at some 100 blows per second. The bar becomes circular in cross-section and swaging is continued until a thick wire about 10 metres long and 1 mm. in diameter is obtained.

The surface of the thick wire is rendered smooth by oxidation preparatory to drawing, which is carried out in over 50 steps ; first through tungsten carbide dies and then through diamond dies at a final speed of 100 metres per minute. The wire is graphite lubricated during drawing and is annealed at various stages. One bar yields about 25,000 metres of 0·001 cm. diameter wire, and from each length of wire 200 mm. samples are taken and weighed accurately to determine the wire diameter.

The checked wire is then coiled on steel or molybdenum mandrels at about 3,000 revolutions per minute to extremely fine tolerances. For coiled-coil filaments this coil is again wound on a second mandrel. The coils are heat treated at various temperatures to relieve strain in coiling and then cut to the required length by a radial knife on a revolving wheel. The mandrels are removed by dissolving in acid.

Filaments are generally handled in batches, or issues, of about 5,000. From each issue produced from one bar, ten or twenty filaments are selected and made into lamps. Current and light output are measured at rated voltage and no issue of filaments is passed to the assembly line until the result of this test indicates that the average and uniformity levels are satisfactory. Life tests are also carried out on these wire trials.

7(*iv*) *The Filling Gas.*

The mixture of argon and nitrogen used in Osram lamps is produced by the Company at its Hammersmith Works (fig. 19). This was the first commercial production of a rare gas in this country. Special precautions have to be taken in its purification, particularly in achieving freedom from water vapour, oxygen, hydrogen and carbon dioxide impurities. In early lamp manufacture the gas was purified and a piped system at low pressure supplied to the exhaust machines in the factory. Today, individual high pressure cylinders, which are each checked for nitrogen content and purity, are used.

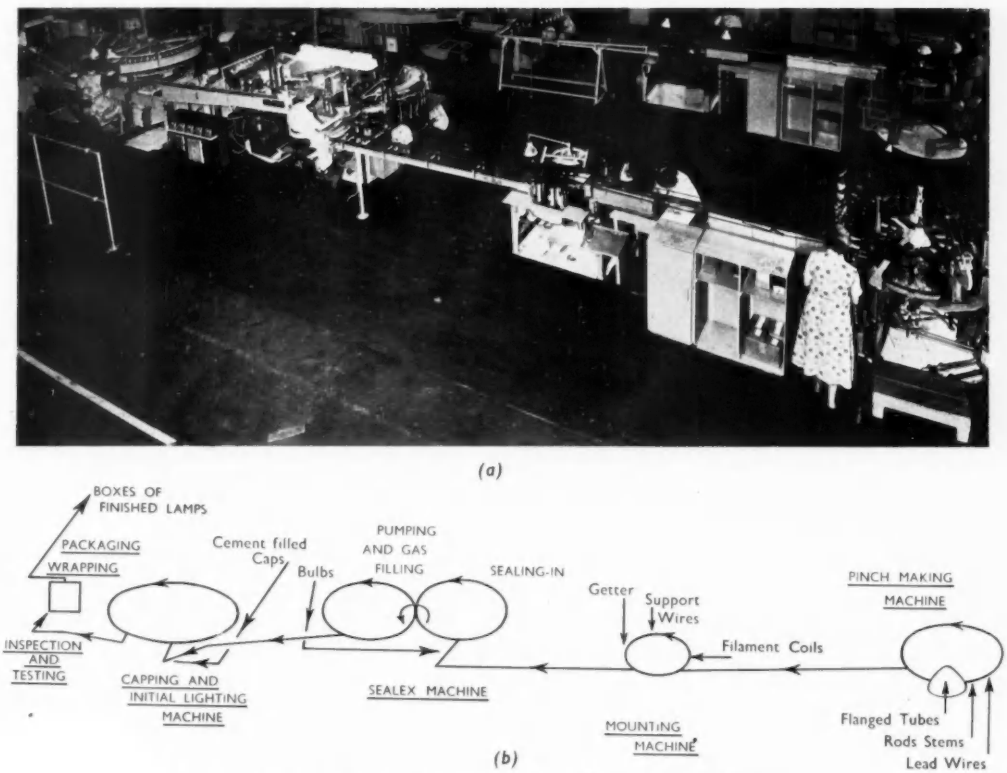


Fig. 20.—(a) A typical G.L.S. lamp production line. (b) Key diagram.

7(*v*) *Lamp Assembly.*

The assembly machines all have work-carrying heads which move intermittently, or " index," through successive positions round a circular periphery. At each position a particular operation is carried out on the

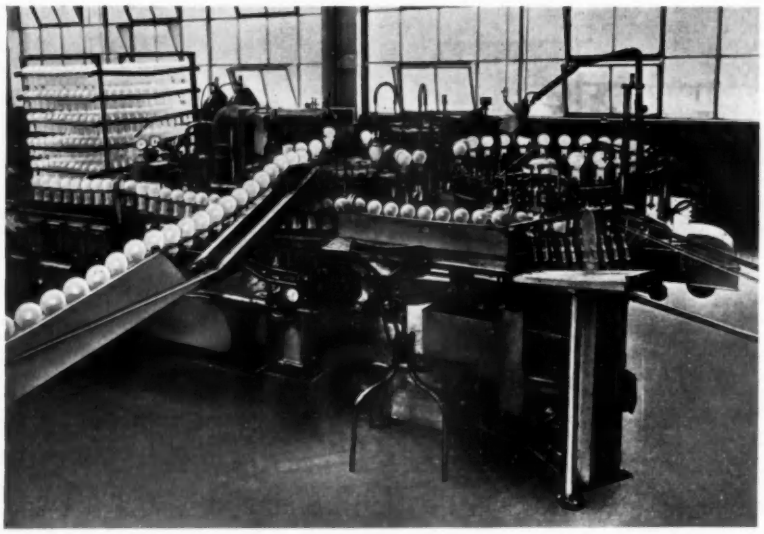


Fig. 21.—The sealing and exhaust machine.

assembled components in the head. All these machines are arranged in a mass production flow line (fig. 20).

The first unit is the pinch or mount-making machine, which has 30 heads and produces about 1,800 pinches per hour. Into this machine are fed the flanged tubes, solid glass rod, exhaust stem, and 4-part lead wires. All these parts are precisely located with respect to each other by the machine and then sealed and pinched together. The pinches are then passed to the filament mounting machine. This ingenious machine, introduced in 1934, prepares the clamping hooks at the lead wire tips and then squeezes the clamps round the filament, which has been picked up by suction and placed in position. The mounted length of coil between the clamps obviously must be very accurately controlled to achieve uniformity of lamp rating. The molybdenum support wires are then automatically inserted into the tip of the supporting glass rod which is made molten by gas flames. The supports are cut to the correct length and wrapped around the filament to form the support hooks. The mounted filament is dipped into a revolving phosphorus getter pot.

The next machine is a composite sealing-in and exhaust machine. Since a lamp is extremely sensitive to water vapour impurity, it was realised early that there should be as little delay as possible between sealing the mount into the bulb and lamp exhausting and filling. These operations are carried out on a combined 2-rotor sealing-in and exhaust machine with 36 heads which was introduced in 1937 (fig. 21 and 22). The exhaust machine operates at the rate of 1,500 lamps per hour and consists of a baking oven, nitrogen flushing and evacuating heads, and a gas filling position. Many pump checks are carried out to ensure high lamp pumping quality and correct gas pressure. The introduction of the machine had a markedly beneficial effect on lamp quality.

From this machine the lamp is passed on to a 48-head capping and initial lighting machine (fig. 23), where the components are caps already filled with a capping

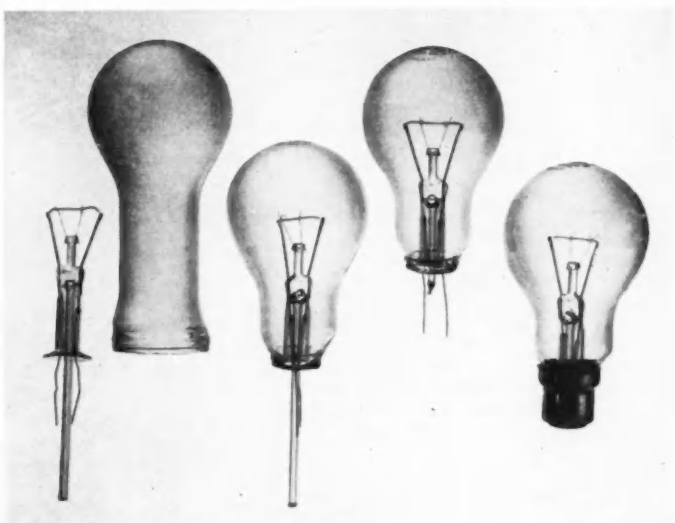


Fig. 22.—Final stages in lamp assembly.

cement and reels of solder fed automatically to solder the cap contacts. The capping cement is of a high quality and carefully manufactured to ensure a high cap torque strength throughout lamp life.

TABLE 2.

Developments in Osram Filament Lamp Making Machinery up to 1950

1920 Machine for forming filament for " squirrel cage " tungsten filament lamps.
1922 8-head pinching machine used for making lamps with exhaust tubes concealed under the lamp cap.
1924 9-head sealing-in machine.
1925 Automatic machine for internal acid etching of bulbs.
1930 Two-way hydraulic machine for the pressing of tungsten and molybdenum powders.
1930 Automatic machine for bulb washing and drying.
1932 12-head machine for coiling tungsten filaments.
1934 Special purpose large drum machine for drawing of tungsten and molybdenum wire.
1934 Special purpose machine for drawing fine diameter tungsten and molybdenum wire.
1934 20-head machine for inserting molybdenum supports and mounting coiled tungsten filaments.
1935 Multi-head machine for sintering tungsten and molybdenum bars.
1935 Improved type lead-in wire joining machine.
1937 Combination sealing-in and exhaust machine.
1938 Automatic machine for glass sleeving of fuse type leading-in wires.
1938 30-head pinching machine with automatic glass and lead-in wire feeds.
1938 60-head machine for capping, soldering and ageing of tungsten filament lamps.
1944 Semi-automatic sealing-in machine—12-head type.

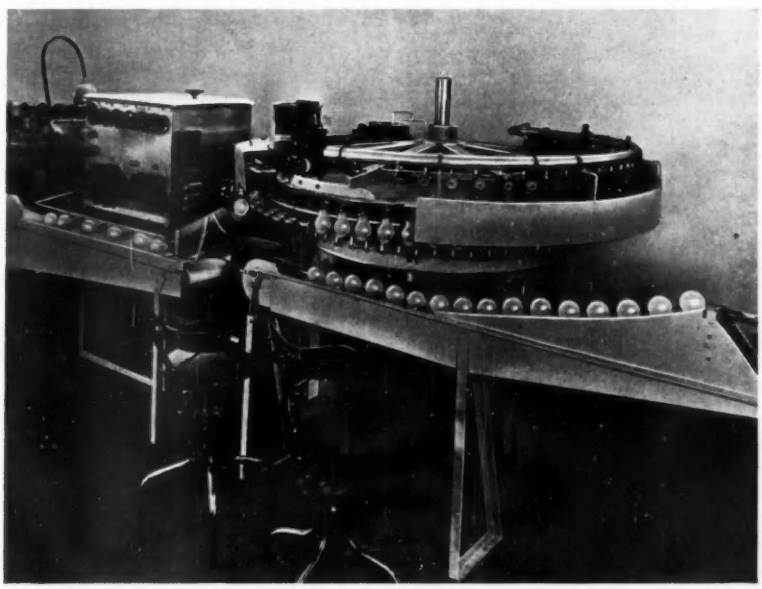


Fig. 23.—The capping and ageing machine.

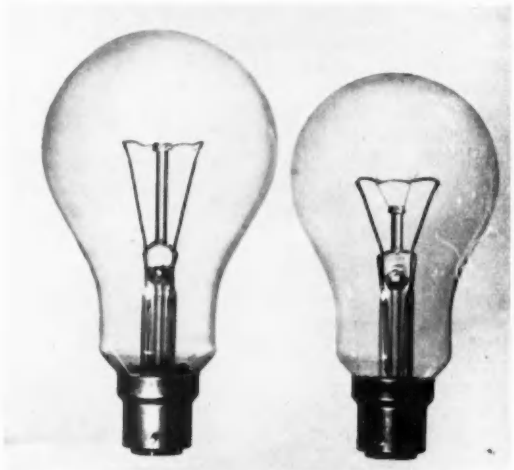


Fig. 24.—Old 100 W lamp compared with the new.

Before being packed, all lamps are tested at the marked voltage rating. Some lamps are taken from each batch at random and checked for filament pitch uniformity, concentricity, light centre length, overall length, cap insulation, and cap torque strength.

8. Inspection and Quality Control.

It has been stressed that close inspection of the product and the process at every stage of manufacture is essential in lamp production, from wire making to the lighted lamp. There are several hundreds of such checks, inspections and measurements, only a few of which have been mentioned.

Since 1930 a growing familiarity with statistical principles has emphasised the weakness of the earlier specifications. The 1934 edition of the British Standard Specification No. 161 introduced for the first time in any specification the limits on variability by specifying coefficients of variation. This specification encouraged the appreciation of the variability in the properties of a product. A re-draft of the specification was under consideration in 1939, but the war prevented its realisation.

The recent edition of April, 1956, replaces averages and coefficients of variation by limits for individual lamps,

such that quality levels are determined by the proportion of lamps falling outside these limits. Small test quantities are also laid down with statistically determined acceptance numbers of lamps outside the limits. This change in method of specification enables the maximum value to be obtained from the independent testing of small batches of lamps purchased on the open market.

9. Development Trends.

The tungsten lamp industry remains a fully dynamic one and there are many plans for expansion and development which are being put into effect rapidly. Before concluding the present account it may be of interest to mention one or two of the present trends.

Performance gains by increasing the gas-filling pressure are being sought and much work has been done by the Company to determine the limit to which lamps may, with full safety, be filled, and to develop techniques for sealing lamps filled to pressures in excess of one atmosphere.

Much thought is being given to the problem of reducing the bulb sizes of general service lamps (fig. 24) and these trends are being internationally discussed with Continental lamp interests with a view to European standardisation. The technical problems involved include the effects on quality of bulb size reductions, the effect on lamp cap temperatures of bulb size changes, the standardisation of lamp temperature measurement methods, the effects on lamp fittings design (especially in optically designed fittings where light centre length is important), the effects on cable temperatures at or near the lamp terminals, and the investigation of the smallest bulb size technically possible and acceptable.

The present article has been concerned mainly with General Lighting Service lamps, but it should be mentioned that much important work is also proceeding on lamps for special purposes such as projection, automobile lighting and other applications.

10. What of the Future?

Although much has been accomplished in the realm of electric incandescent light sources, much remains to be achieved. The theoretical maximum efficiency for a " full " radiator occurs at an operating temperature of around 6,000 deg. K., when the efficiency is 84 lumens per watt. The efficiency of a household general service lamp with a thousand hour life is less than 15 lumens per watt, and the maximum efficiency of any practical tungsten lamp is about 30 lumens per watt. The practical limits are set by the physical properties of the incandescent material ; its melting point, its evaporation rate at high temperature and its electrical resistivity. No satisfactory replacement for tungsten has been found over the last forty years, although the low resistivity of tungsten necessitates its use as a very fine wire to give the desired electrical characteristics. However, the technological environment of the lamp industry has advanced considerably in this time and much effort throughout the world is now being spent on developing stable high temperature materials in connection with the nuclear energy and aeronautical programmes. Such developments are being closely watched, since they may have some bearing on the incandescent light source. Marked improvements in efficiencies may be possible, even with tungsten, by new methods of controlling the evaporation process.

The understanding of the basis of the properties of materials in the solid state has also developed very rapidly in the last decade. This understanding may help the lamp engineer to fabricate refractory materials which emit, when heated, a higher proportion of radiation in the visible region, and therefore yield a higher luminous efficiency.

Thus, the incandescent lamp industry, which contributed so much to the establishment of the present technological era, may itself benefit from the fruits of technology in the industries to which it gave birth.

Crushing and Screening Plant at a Derbyshire Lime Works

By A. R. SINCLAIR and D. J. MURRELLS, A.M.I.Mech.E.,
Erith Engineering Works.

THE limestone quarry of Beswick's Lime Works Ltd. has recently been equipped with a fully mechanised crushing and screening plant which is one of the most up-to-date installations of its kind in the quarrying industry. The plant, including the buildings, was supplied by the Erith Engineering Works of the G.E.C. to the general specification of Beswick's Lime Works Ltd.

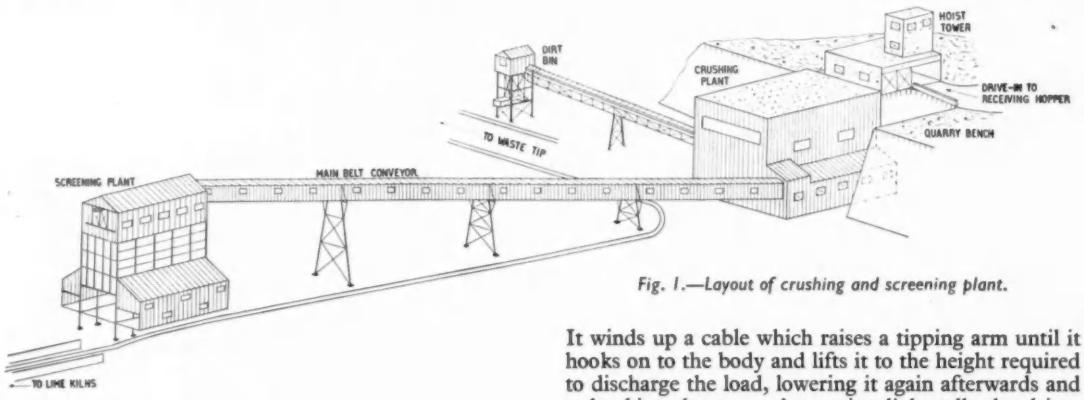


Fig. 1.—Layout of crushing and screening plant.

The quarry is situated at Hindlow, about 3 miles south of Buxton, and works beds of high-grade carboniferous limestone. The limestone, after blasting, contains all sizes of rock up to very large pieces about 2 cu. yd. in volume. In addition, a variable quantity of dirt and clay is sometimes present. The broken rock is loaded by means of a 2½-cu. yd. electrically-driven excavator into 12-ton Foden dumpers equipped with specially built side-tipping bodies. A diesel-engined bulldozer is used to clean up the floor.

The dumpers, three in number, transport the rock to the plant at the rate of 200 tons per hour. Fig. 1 shows the general layout. The crushing plant is adjacent to the quarry, with the dirt bin a short distance away at one side. The screening plant and loading bins are about 125 yd. away in line with the kilns, which are some 200 yd. beyond them.

CRUSHING PLANT.

The arrangement of the crushing plant can be seen in fig. 2. At the head of the plant, on the level of the quarry floor, is a feed hopper into which the dumpers tip their loads. The rock drops on to a 6 ft. wide variable-speed pan feeder protected by a curtain of heavy chains. The dumpers are not provided with a tipping mechanism but are unloaded by means of a stationary automatic motor-driven winch situated in a housing over the covered entrance to the hopper.

The winch is operated by a pushbutton control within reach of the driver's cab, as shown in fig. 3. It winds up a cable which raises a tipping arm until it hooks on to the body and lifts it to the height required to discharge the load, lowering it again afterwards and unhooking the arm. A warning light tells the driver whether the body is hooked or clear. This side-tipping method enables the lorries to be spotted alongside the hopper without manoeuvring and to drive forward out of the plant after unloading, leaving the road clear for the next to drive in. In this way a tipping rate of 12 tons of rock every 3 to 4 minutes can be maintained without difficulty.

The pan feeder below the hopper discharges on to a steep chute placed at right angles to it in line with the crusher. Heavy curtains of chains and steel billets are provided to check the fall of the large pieces. The rock falls on to a heavily-built Sherwen electromagnetic vibrating feeder, which delivers it with a minimum of shock to a 5-roll grizzly having 6 in. square apertures, evening out the flow at the same time. The small stone drops through the grizzly with the bulk of the clay and dirt, which must be removed from the limestone rock.

The roll grizzly discharges the 6 in. oversize on to a chute with a chain curtain through which it passes into a 54 in. × 42 in. jaw crusher set to break it all below 8 in. size. This machine, which is illustrated in fig. 4, is designed for very heavy duty. It is driven by a 170 h.p. motor through V-belts. The swing shaft bearings and the other bearing surfaces are lubricated automatically either with grease or oil under pressure by

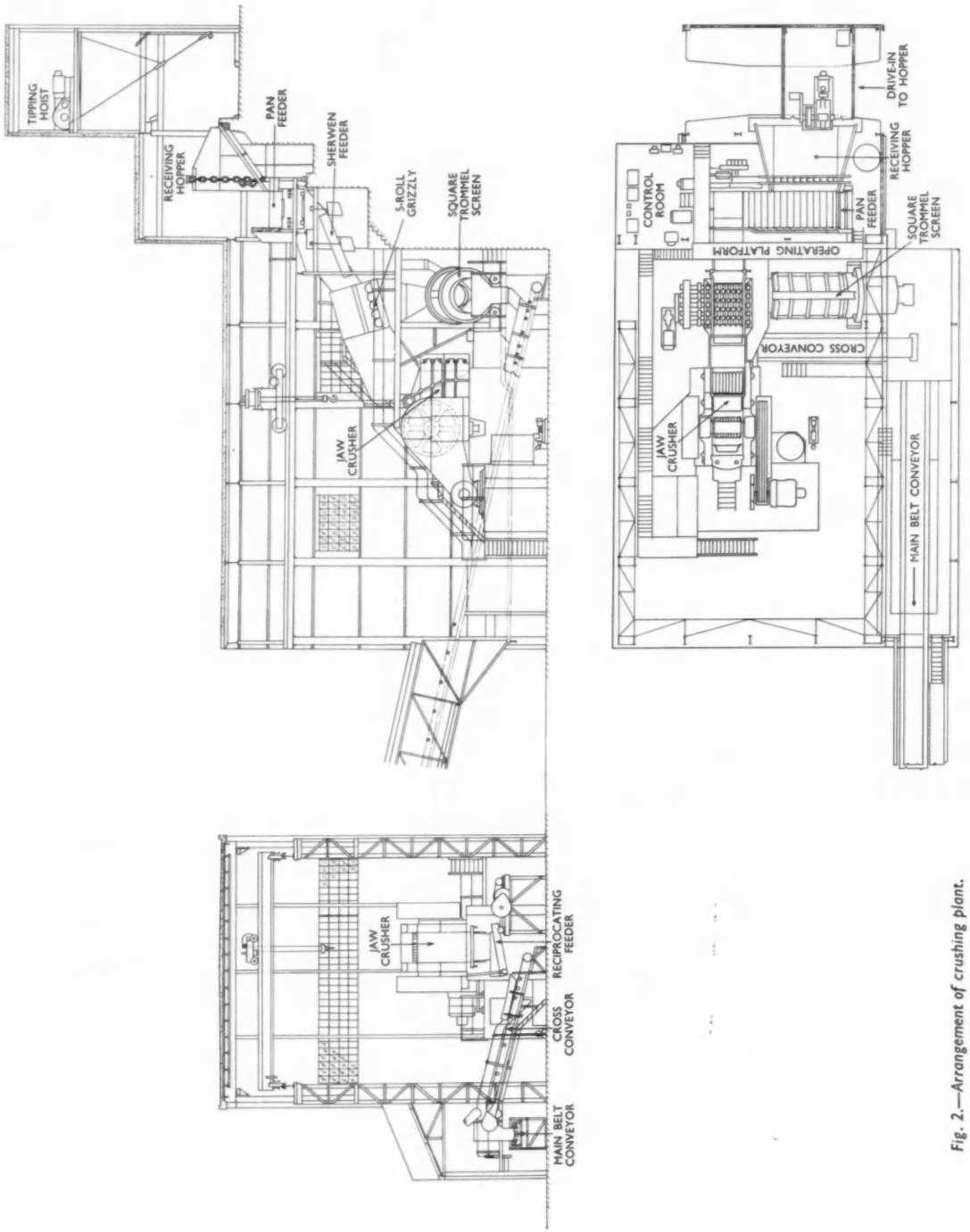


Fig. 2.—Arrangement of crushing plant.

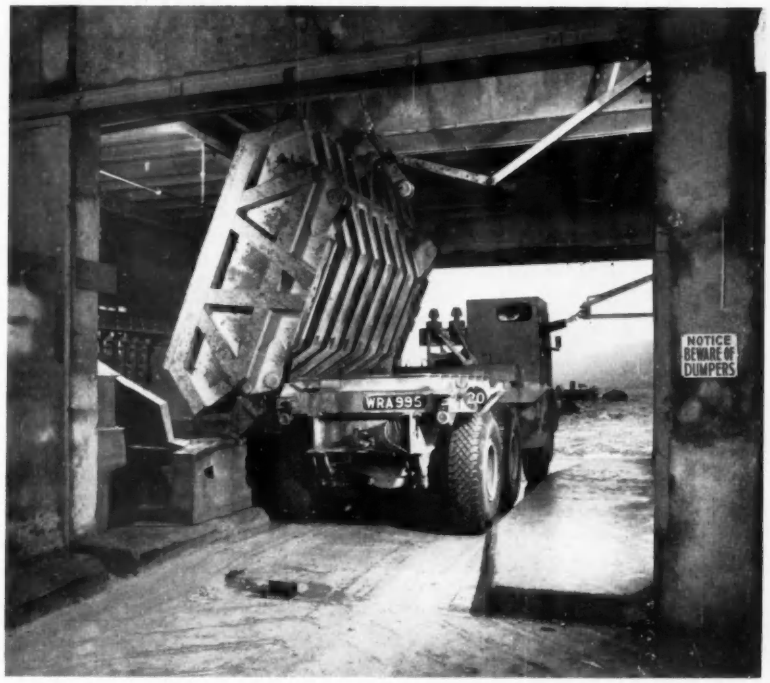


Fig. 3.—Dumper being tipped by pushbutton control from driver's cabin.

means of two pumps driven from the pitman cap. This discharge from the crusher drops on to a reciprocating feeder, which takes the impact of the falling rock and delivers it at a relatively even flow to a cross belt conveyor. This transfers it to the main belt conveyor which elevates clean stone to the screening plant.

The 6 in. undersize from the roll grizzly drops direct into the feed end of a revolving trommel screen of unusual design, the basic principle of which was conceived by the engineering staff of Beswick's Lime Works Ltd. The construction of the screen can be seen in fig. 5. The screen is square, with sides 4 ft. wide by 23 ft. long constructed of steel plates with 3 in. round holes. It is mounted on rubber-tyred rollers at an inclination of 7° and revolves at 13 r.p.m. Any loose undersize falls through the holes as the screen rotates, but the sticky dirt bound with clay slides down the rising side of the screen and is punched out at the bottom through the holes in the plate at right angles to it by the impact of the falling mass. The dirt falls on to a short belt conveyor feeding on to a long inclined conveyor. This elevates it to a dirt bin, whence it is discharged by a 48 in. apron feeder into Decauville wagons for transport to the waste tip. The 3 in. oversize is discharged direct on to the main belt conveyor elevating the clean stone to the screening plant.

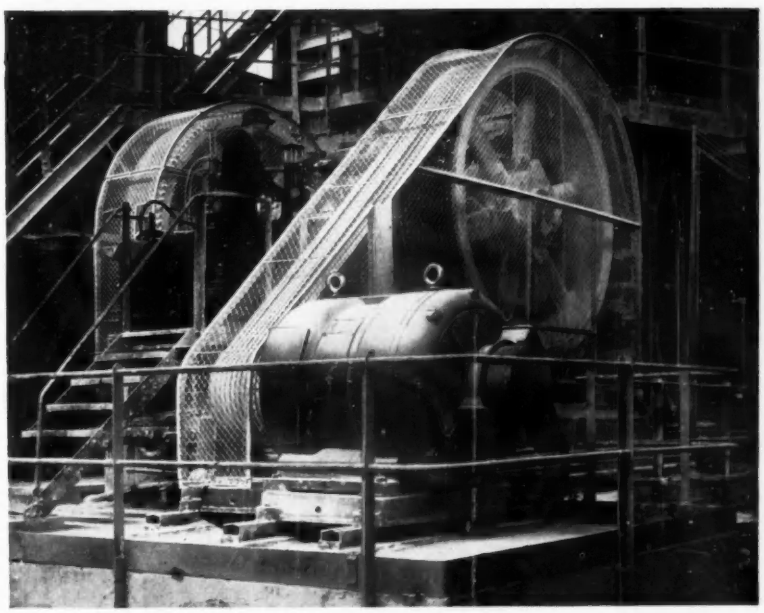


Fig. 4.—54 in. x 42 in. jaw crusher.

SCREENING PLANT.

Clean stone from the main conveyor is fed into a revolving trommel screen 5 ft. in diameter and 40 ft. long, fitted with steel plates with 3 in. and 5 in. round holes (fig. 6). Like the square screen in the crushing plant, it is mounted on rubber-tyred rollers. It is situated at

Fig. 5.—Trommel screen, 4 ft. square x 23 ft. long, for removing clay and dirt.

the top of the building over bunkers with a total capacity of 1,000 tons, which are spaced to receive the three sizes of stone that are produced, i.e. plus 5 in., minus 5 in. plus 3 in., and minus 3 in. Each of the two larger sizes is withdrawn as required by means of 36 in. wide variable-speed apron feeders into Decauville wagons running on a light rail track that leads to the lime kilns. The minus 3 in. product is discharged through a swing gate.

CONTROL.

A control room has been built by Beswick's Lime Works at the level of the pan feeder in a position giving a clear view of the whole plant. It is kept under a slight pressure of air to exclude dust. The switchgear is interlocked in such a way that the machines and conveyors can only be started in a sequence that begins with the trommel screen making the final sizing and proceeds backwards through the plant. In addition to the switches in the control room, stop buttons for emergency use are placed at selected spots. These enable an operator to stop any machine, if necessary, together with the whole of the flow towards it.

MAINTENANCE.

Special attention was paid to accessibility in the design stage. Adequate space has been provided round every machine for maintenance and repairs, and room has been left for the direct off-loading and storage of stores and spares within the crusher building.

The crushing plant has been painted in bright and attractive colours and every part of the interior is illuminated by a well conceived system of lighting. The whole aspect of the plant is one of spaciousness and cleanliness.

ACKNOWLEDGMENT.

The authors are indebted to Beswick's Lime Works Ltd. for their co-operation in photographing the plant and for their permission to publish this article.

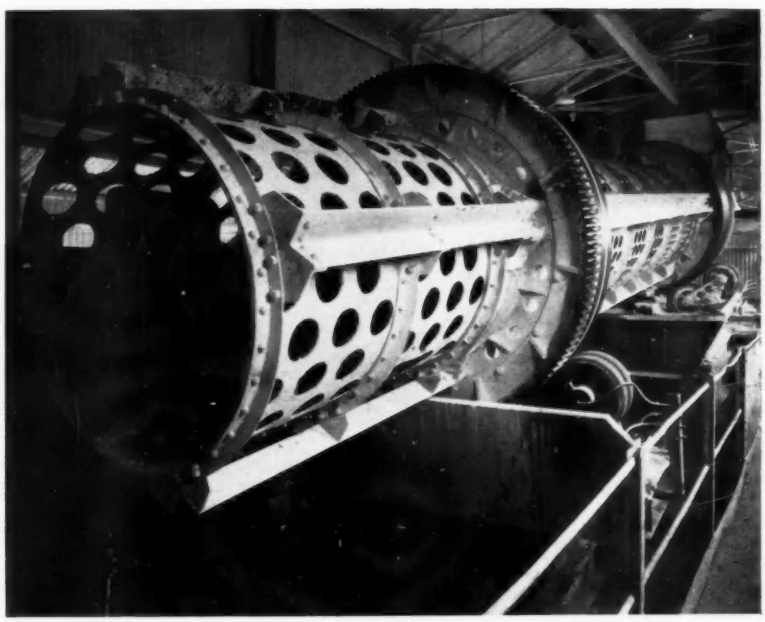


Fig. 6.—Trommel screen, 5 ft. diam. x 40 ft. long, for sizing clean stone.

Uranium Production in South Africa

By PHILIP RABONE, A.R.S.M., D.I.C., M.I.M.M.,
Erith Engineering Works.

The occurrence of uranium minerals and the economics of uranium production from low-grade ores, such as occur in South Africa, are discussed very briefly. The process by which the uranium oxide is extracted from these ores is described in more detail. It comprises acid leaching of the ore, the separation of the uranium from the other constituents in solution by ion exchange, its precipitation, and finally its calcination to the oxide, U_3O_8, in a form suitable for shipment.

ALTHOUGH uranium is not an uncommon constituent in the earth's crust, it is for the most part finely disseminated in the form of an oxide mineral throughout a wide variety of igneous rocks. Rich deposits, mainly in vein formations, occur in only a few localities, notably in the Belgian Congo, Canada, and the United States. Until five or six years ago, the mines in the first two of these countries were practically the only source of supply, but since then the greatest reserve of uranium in the world has been developed from the comparatively low-grade gold-bearing reefs of the Transvaal and Orange Free State in South Africa.

OCCURRENCE OF URANIUM IN SOUTH AFRICA.

The uranium minerals occur in the reefs of the Witwatersrand, which have been mined for gold for the past 60 years, and in similar reefs in the more recent mines of the Orange Free State, the uraniferous minerals being closely associated with the gold. The uranium is present in the ore as uraninite, a blackish crystalline mineral which is a mixture of UO_2 and UO_3. Its content is normally expressed in terms of U_3O_8, i.e. $UO_2.2UO_3$, which represents the final uranium oxide product as shipped from the mines.

ECONOMICS OF URANIUM MINING.

With one or two exceptions the uranium-bearing gold ores are mined primarily for gold. Their uranium content varies from approximately $\frac{1}{4}$ to $2\frac{1}{4}$ lb. of U_3O_8 per ton of ore, averaging 0·7 lb. per ton over the combined fields of the Transvaal and Orange Free State.

The richer reefs are few in number and are all low in gold, but they contain enough uranium to make its extraction from the ore a profitable operation. The rest of them contain insufficient uranium to be mined for this metal alone, but the association of the uraninite with gold in payable quantities makes it practicable for the uranium to be extracted from what would otherwise be an uneconomical source, provided that the ore contains not less than about $\frac{1}{4}$ lb. of U_3O_8 per ton of ore. It is this combination of gold with uraninite which has made South Africa the largest prospective producer of uranium oxide in the world.

PRODUCTION IN SOUTH AFRICA.

Uranium production began in South Africa in October, 1952, when the first plant of the Witwatersrand was started up at West Rand Consolidated Mines

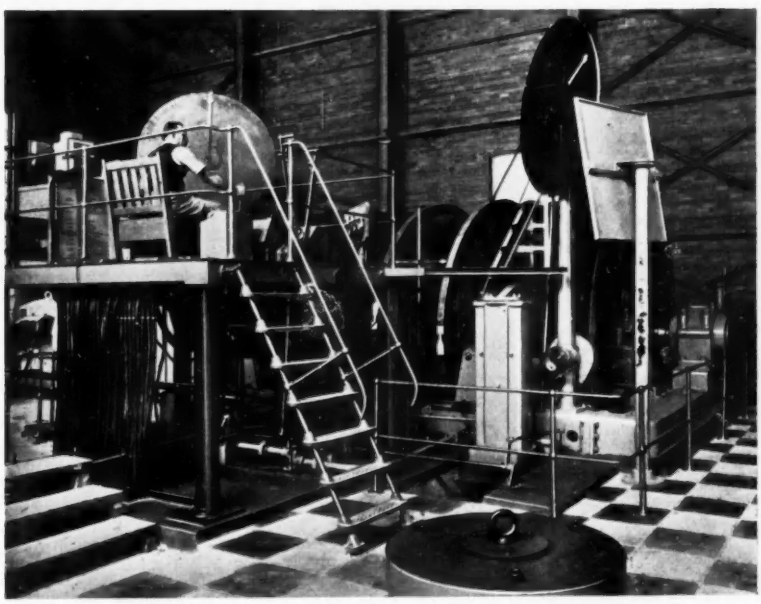


Fig. 1.—Winding engine at the Monarch Shaft of West Rand Consolidated Mines Ltd.

Ltd. The Monarch Shaft at this mine was the first to be sunk exclusively for hoisting uranium ore. The double drum winder with which it was equipped was supplied by the Erith Engineering Works of the G.E.C. and began duty during sinking operations, contributing, in September, 1955, to the achievement of the record monthly footage sunk of 763 ft., which at that time was a world record for all types of shaft. The winding engine is illustrated in fig. 1.

Only four mines had been scheduled by the South African Atomic Energy Board as uranium producers by 1952. The new industry made rapid strides, however, and by the end of 1957 seventeen plants were in production or in the course of erection in the Transvaal and Orange Free State, and uranium oxide was being exported to the value of £40 million annually.

Fig. 2.—Uranium leaching plant in South Africa showing Pachuca tanks on the right and contact acid plant in the left background.

EXTRACTION PROCESS.

Although uranium is multivalent, the only compounds that are stable in solution are quadrivalent or hexavalent. The quadrivalent oxide UO_2 is not soluble enough in acids or alkalis for practical purposes, but the hexavalent trioxide UO_3, which can be regarded as uranyl oxide, UO_2O, is readily soluble in both acids and alkaline carbonate solutions, and both of these are commonly employed for extracting uranium from its ores or concentrates, with the addition of a strong oxidising agent to convert the UO_2 to UO_3. Leaching in a solution of sodium carbonate is, in general, only employed with ores containing acid-consuming constituents such as limestone and dolomite. Acid leaching is normally less costly despite the expense of having to make most of the plant of acid-resistant material. It is practised in all the South African plants, sufficient pyrite being obtainable from the mines to manufacture sulphuric acid for the whole field. Pyrolusite, containing about 40 per cent of available MnO_2, is obtainable locally and is used as the oxidising agent. The reactions by which the uranium is dissolved can be expressed as follows :

$$UO_3 + H_2SO_4 \longrightarrow UO_2SO_4 + H_2O$$

$$UO_2 + 2H_2SO_4 + MnO_2 \longrightarrow UO_2SO_4 + MnSO_4 + 2H_2O$$

In the uranium-producing mines of the Witwatersrand and the Orange Free State the gold is nearly always recovered first. It is dissolved in a solution of sodium or calcium cyanide after the ore has been ground to what is termed a slime, which is roughly below 100 mesh (0·006 in.) in size with 65-75 per cent through 200 mesh (0·003 in.). The uraninite is substantially free at this size and can therefore be dissolved out of the residue from cyanidation without further grinding. The dewatered gold-free residue from the cyanide section constitutes the feed to the uranium plant, a general view of which is shown in fig. 2. The residue is diluted with mine water to a pulp, as it is termed, with a consistency of about 50 per cent of solids, and pumped to a stock tank at the head of the uranium plant.

At some mines payable amounts of uranium are contained in dumps of cyanide residue from past operations. In such cases the slime is reclaimed by hydraulic monitors and the pulp is pumped to the stock tank where it mixes with the current cyanide residue. In addition, a number of plants receive current and reclaimed cyanide residues, rich enough in uranium to be profitable, from neighbouring mines which are too small to warrant the erection of leaching plants of their own. The residues are pumped through long pipelines to metering tanks in the central plant and then transferred to the stock tank. The uranium plants erected so far vary in capacity from about 3,500 to over 10,000 tons of total feed per 24 hours.

LEACHING PLANT.

The circuit of a typical uranium leaching plant is given in fig. 3. The stock tank at the head of the plant is generally cylindrical in shape, 45-50 ft. high and 25-33 ft. in diameter with a conical bottom, at the apex of which is an air-lift to keep the pulp in suspension ; they are known as Pachuca tanks, or, more simply, as Pachucas. Less frequently, shallower

circular tanks are employed, 45-50 ft. in diameter, with stirring arms in the bottom. As the pulp still contains some cyanide and lime, it is first dewatered on vacuum filters of the drum type to remove these constituents and any other soluble salts that may be present.

The filter cake is re-pulped with acid filtrate from the second stage of uranium filtration and pumped at a density of 50-60 per cent solids to the leaching tanks, through which it passes continuously in series. These can be seen in fig. 2. They consist of rubber-lined Pachucas more or less of the same size as the stock tank. The pulp enters at the top on one side and is carried down into the tank by the circulation of the air-lift, overflowing continuously at the opposite side under the pressure of incoming feed. Given good circulation, short-circuiting across the top does not occur. The number of tanks is sufficient to give a contact time with the acid varying from 18 to 30 hours according to the nature of the ore. Batch operation is sometimes practised when more accurate control of leaching is necessary. In this method the tanks are run independently, being filled and discharged one at a time in turn.

The amount of acid required depends on the class of ore ; it averages about 50 lb. per short ton of ore throughout the field. The bulk of it is added to the first Pachuca, but small amounts may be needed at a later stage to maintain the acid strength, which should not be allowed to fall below about 5 grammes of sulphuric acid per litre of solution. The pyrolusite is not put in at the start of the leach on account of the presence of reducing gases, chiefly hydrogen. These are generated by the action of the acid on the fine steel that enters the pulp through the abrasive action of the ore on the balls in the grinding mills of the cyanide plant. Hydrogen sulphide may also be generated by reaction of the acid with any pyrrhotite that may be present in the ore. If these gases were allowed to come in contact with the manganese dioxide, the consumption of pyrolusite would be unduly high. They are dissipated fairly quickly by the airlift, and it is usually safe to add the pyrolusite to the second Pachuca of the series. The first tank is not wasted as far as dissolution is concerned, because the UO_3 in the uraninite starts to dissolve without an oxidiser.

The degree of oxidation is checked at intervals in each Pachuca by estimating the ferric and ferrous iron in solution. Too small a proportion of ferric iron indicates insufficient oxidation ; it should normally amount to at least 50 per cent of the total iron. The available acid is estimated at the same time and the strength made up to about 5 grammes per litre if necessary. The consumption of pyrolusite is usually about 25 lb. per ton of ore (10 lb. available MnO_2).

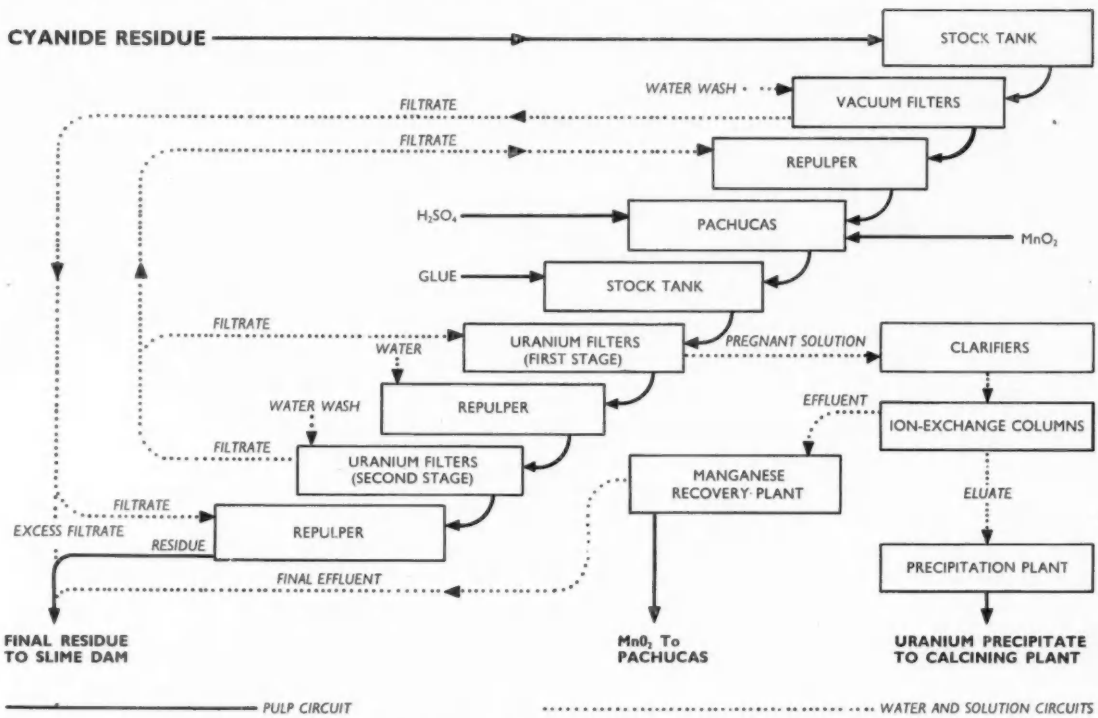


Fig. 3.—Circuit of uranium leaching plant.

The pulp overflowing the last Pachuca tank of the series is pumped to a stock tank ; in the case of batch leaching it is pumped from the bottom of the tank after the necessary number of hours' leaching. All the recoverable uranium is now in solution and has to be separated from the barren solids. This operation is carried out in rotary vacuum drum filters constructed of stainless steel (fig. 4). As the pulp contains colloidal silica, some animal glue is added at the pump to coagulate it ; otherwise filtration would be virtually impossible. Even with glue it is not possible to remove all the uranium in solution from the solids, some 30 per cent of it still remaining in the cake. Filtration is therefore carried out in two stages. The bulk of the uranium-bearing solution is filtered off in the first stage in rows of filters in parallel, with a heavy wash of secondary filtrate on the cake to displace as much uranium as possible. The filtrate that comes off may contain up to 1·5 grammes of uranium sulphate per litre. This is termed the pregnant solution and is sent to ion-exchange columns for extraction of its uranium content. The filter cake is re-pulped and a second stage of filtration is carried out in similar rows of filters with a water wash on the cake. The filtrate from this stage, which contains the rest of the uranium, is not rich enough to be sent to the ion-exchange columns. It is therefore returned to the leaching circuit and first-stage filters as shown in fig. 3, where it picks up more uranium and emerges as pregnant solution.

The barren residue from the second stage of filtration is re-pulped with water and pumped to a slime dam with the addition of enough lime to neutralise any residual acid. There the solids are settled out and stacked. If the residue should contain pyrite, however, this is first recovered by flotation and sent to a contact acid plant for conversion into sulphuric acid. The flotation tailing then constitutes the final residue and is pumped to the slime dam.

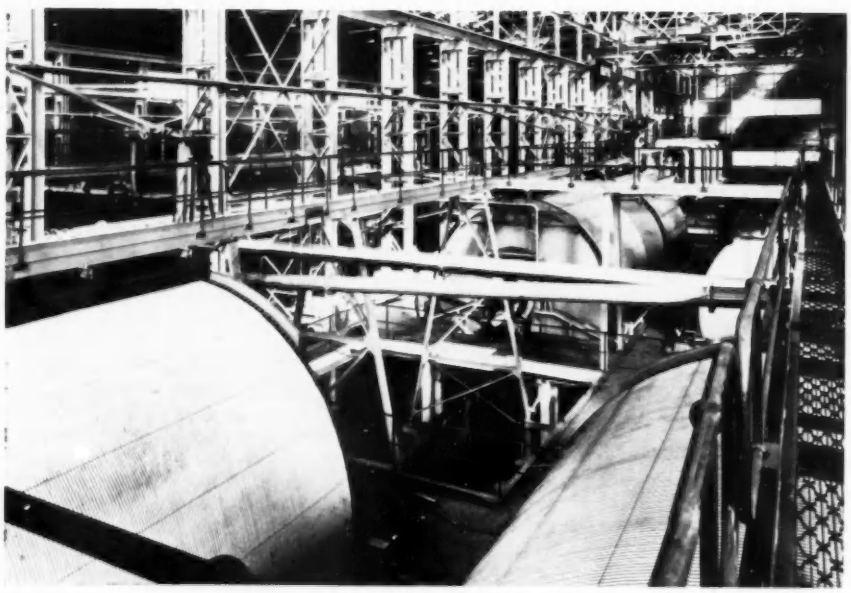


Fig. 4.—Uranium plant filters.

RECOVERY OF URANIUM BY ION-EXCHANGE.

The pregnant solution from the first stage of uranium filtration contains from about 0·5 to 1·5 grammes of UO_2SO_4 per litre, together with a much larger quantity of sulphates of iron (ferrous and ferric), manganese, aluminium and magnesium, all dissolved from the ore. The iron sulphates alone may amount to ten times the concentration of uranium sulphate. The problem of recovering the uranium from this solution in a relatively pure form was not easy to solve, because the salts of iron and uranium are so similar in their properties that they cannot be separated by any simple chemical reaction. At the time when uranium production was being started in South Africa, the ion-exchange method was the only one that held out much promise and it proved to be so successful that it is now in universal use in all the uranium plants there.

Ion-Exchange Resins.

Resins of a special type are employed in the ion-exchange process. They may be visualised as sponge-like structures with millions of minute pores of molecular size into which water is capable of penetrating.

The skeleton of the resin structure consists of a material similar to the plastic polystyrene, which has been subjected to a process of cross-linking to render it tough and chemically stable. It is made in the form of beads about $\frac{1}{16}$ in. in diameter. Bonded to the surface of all the pores are closely-spaced groups which are capable of ionising in water to form either positively or negatively charged points of activity, according to the type of resin.

Cation Exchange.

In cation-exchange resins the groups may consist of such compounds as sulphonates with a formula which may be written as $R\text{-}SO_3Na$, where R represents the body of the resin. In water this is capable of ionising into $R\text{-}SO_3^-$ and Na^+. The cation (positive ion), Na^+, floats off and can be replaced by another ion with a similar charge, but the anion (negative ion) remains attached to the resin surface. Since the uranyl sulphate in the pregnant solution dissociates into cations of UO_2^{++} and anions of SO_4^{--}, the cation with its two positive charges might be expected to attach itself to two of the negative points on the resin, thus :

$$\begin{matrix} R\text{-}SO_3 \\ \qquad\quad UO_2 \\ R\text{-}SO_3 \end{matrix}$$

This attachment does in fact happen. Unfortunately other ions in solution are also absorbed, especially ferric cations, Fe^{+++}, which anchor themselves even more firmly than the uranyl ions. As a consequence no effective separation can be obtained with cation-exchange resins.

Anion Exchange.

During the ion-exchange investigations it was found that some of the uranyl ions combine with excess sulphate ions from the sulphuric acid to form a more complex anion possessing four negative charges in accordance with the following equation :

$$UO_2^{++} + 3SO_4^{--} \rightleftharpoons [UO_2(SO_4)_3]^{----}.$$

The equilibrium between the two sides of the equation is explained later.

Further research showed that the complex anion could be extracted from solution by certain anion-exchange resins. These have the same porous structure as the cation-exchange resins, but the exchange groups are amine salts which give positively charged active points in solution. Amberlite I.R.A.400 and De-Acidite FF are most commonly employed. They may be represented by the formula :

$$\begin{matrix} CH_3 & CH_3 \\ \quad\diagdown & \diagup \\ \quad R\text{-}CH_2\text{-}N\text{-}Cl \\ \quad\quad | \\ \quad\quad CH_3 \end{matrix}$$

This can be written more simply as $R\text{-}Cl$, R representing the whole of the organic structure of the resin. In solution it dissociates into R^+ with a positive charge, which remains as an active point on the resin, and Cl^-, which is free-floating within the structure and can be replaced by another anion. Thus the points of activity on the resin are positively charged, and the uranyl sulphate anions become attached in the way that is indicated diagrammatically in fig. 5. Sulphate ions in solution, SO_4^{--}, which outnumber the uranyl complex ions, are capable of attaching themselves to any two adjacent and unoccupied active points, but they have

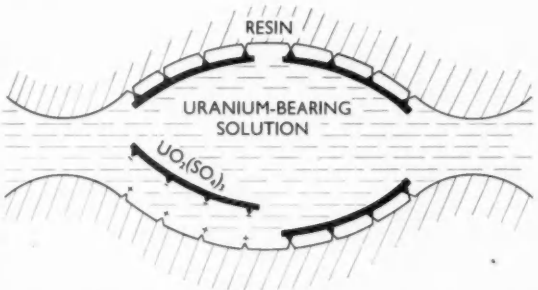


Fig. 5.—Diagram illustrating absorption of uranyl sulphate ions by an ion-exchange resin.

less affinity for the resin than the complex ions and are quickly elbowed out of the way.

Absorption Affinity.

Each type of ion has its own particular affinity for a resin, but its tendency to be absorbed is also proportional to its concentration in the solution. When two types of ions are competing for places on the resin, those with a very high affinity may be preferentially absorbed, even though their concentration is less than those with a lower affinity. If those with the higher affinity also have a higher concentration, they are very strongly absorbed. The affinity depends on several factors, the principal of which is valency, increasing valency giving greater affinity. Second in importance is ionic size. As the uranium complex has four valencies and is, in addition, a very large ion, it has an extremely high affinity for the resin. It is therefore held preferentially even in the presence of a large excess of sulphate or bisulphate ions.

Ferric ions, Fe^{+++}, and cations of other metals in the solution cannot become attached to the active points because, being positively charged, they are repelled. There are some basic ferric sulphate anions, $FeOH(SO_4)_3^{---}$, in the solution, but, being smaller in size and possessing only two negative charges, they are elbowed out by the uranyl sulphate ions and very few remain absorbed by the resin.

Ion-Exchange Cycle.

The exchange reaction is carried out in closed rubber-lined cylinders, known as columns, into which the beads of resin are loaded. They are operated in groups of three, and the plant usually contains three or four such groups with one group spare. In a medium-sized uranium plant treating about 4,000 tons of ore per day, the columns are usually about 7 ft. in diameter

by 12 ft. high. Fig. 6 shows some of the columns in a South African installation.

The pregnant solution is divided equally between the groups. The cycle is the same for all, but each group runs independently. A complete cycle is shown diagrammatically in fig. 7. In the first stage (fig. 7(a)) the solution is introduced at the required rate into the top of column 1. It travels slowly through, filling up the resin with uranium from the top downwards, and then passes into the top of column 2, which catches any uranium escaping from column 1 when the latter is nearing its full load. The timing of the cycle is such that the second column of the loading circuit never becomes overfull and the effluent discharge at the bottom is therefore always uranium-free. While column 1 is being loaded, the uranium in the previously saturated column 3 is removed by elution, as described later.

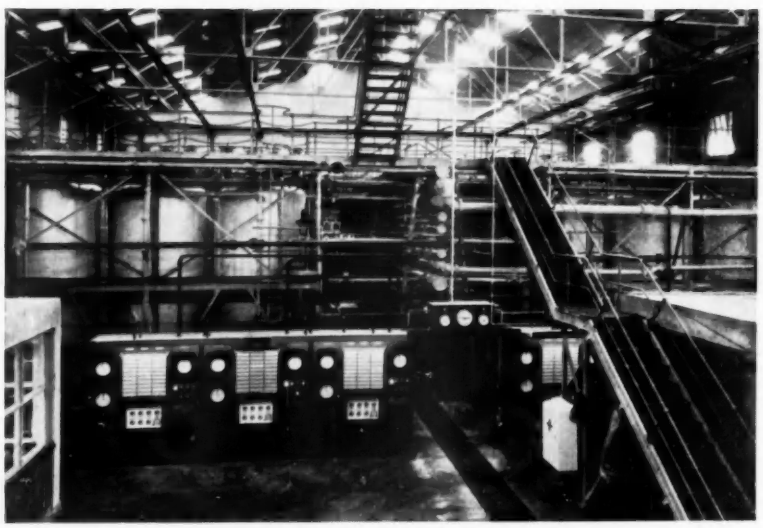


Fig. 6.—Ion-exchange columns and automatic control panels in a South African leaching plant.

As fast as the uranyl sulphate anion is absorbed by the resin, more of it is formed from the component ions in the solution. This is because, in given conditions, there is always a definite equilibrium between the uranyl cations and the complex anions in the reaction $UO_2^{++} + 3SO_4^{--} \rightleftharpoons [UO_2(SO_4)_3]^{----}$.

As the complex anion is absorbed by the resin, more is formed from the component ions to restore the equilibrium, the free acid supplying the necessary sulphate ions for the reaction. Thus there is always some of the complex ion available for absorption down to the very last trace of UO_2^{++}.

When column 1 is saturated, i.e. when the solution leaving at the bottom shows the same concentration as the incoming pregnant solution, it is cut out of the circuit and the second stage is commenced as shown in fig. 7(b). The pregnant solution is turned into column 2 with column 3 in series with it, and the elution of column 1 is started. The change-over is fully automatic. Once the time-cycle has been determined for a particular plant, the necessary valves are opened or closed in the correct sequence at predetermined intervals by an automatic control system. Periodical analyses of the pregnant solution and effluent are made, but their purpose is to check the timing, not to control it, although an overriding hand control is available if required.

The loading of column 2 is continued for the same time as before. During this stage column 1 is eluted and is ready for the third stage by the time that column 2 is saturated. The latter is then cut out and eluted, while loading is continued as in fig. 7(c) with columns 3 and 1 in series. The end of the third stage, with column 3 fully loaded, marks the completion of the cycle. The change-over brings the circuit back to fig. 7(a) and the commencement of a new cycle.

The removal of the uranium from the resin by elution is the reverse of its absorption. It cannot be accomplished efficiently, however, in a sulphate solution. The affinity of the complex uranyl sulphate ion for the resin is so high that complete elution could not be effected even by increasing the concentration of sulphate ions to the maximum possible. The affinity of the complex ion must, therefore, be reduced or destroyed. This is accomplished by passing through the column a comparatively strong chloride or nitrate solution. The effect is to break up the complex into its component ions of UO_3^{++} and SO_4^{--}. The uranyl ions are immediately repelled and detached from the positive points on the resin, and they tend to form a salt, such as UO_2NO_3, with the anions. The sulphate ions are replaced on the resin by chloride or nitrate ions because the latter are present in a much higher concentration. Thus the uranium is completely eluted by the passage of the solution through the column.

In South Africa ammonium nitrate is readily available and is invariably employed for elution. A slightly acid normal solution is used containing from 0·9*N* NH_4NO_3 and 0·1*N* HNO_3 to 0·67*N* NH_4NO_3 and 0·33*N* HNO_3. This is run through the column from the top at a rate which is calculated to remove all the uranium before the next change-over in the cycle is due, enough time being allowed to wash the resin

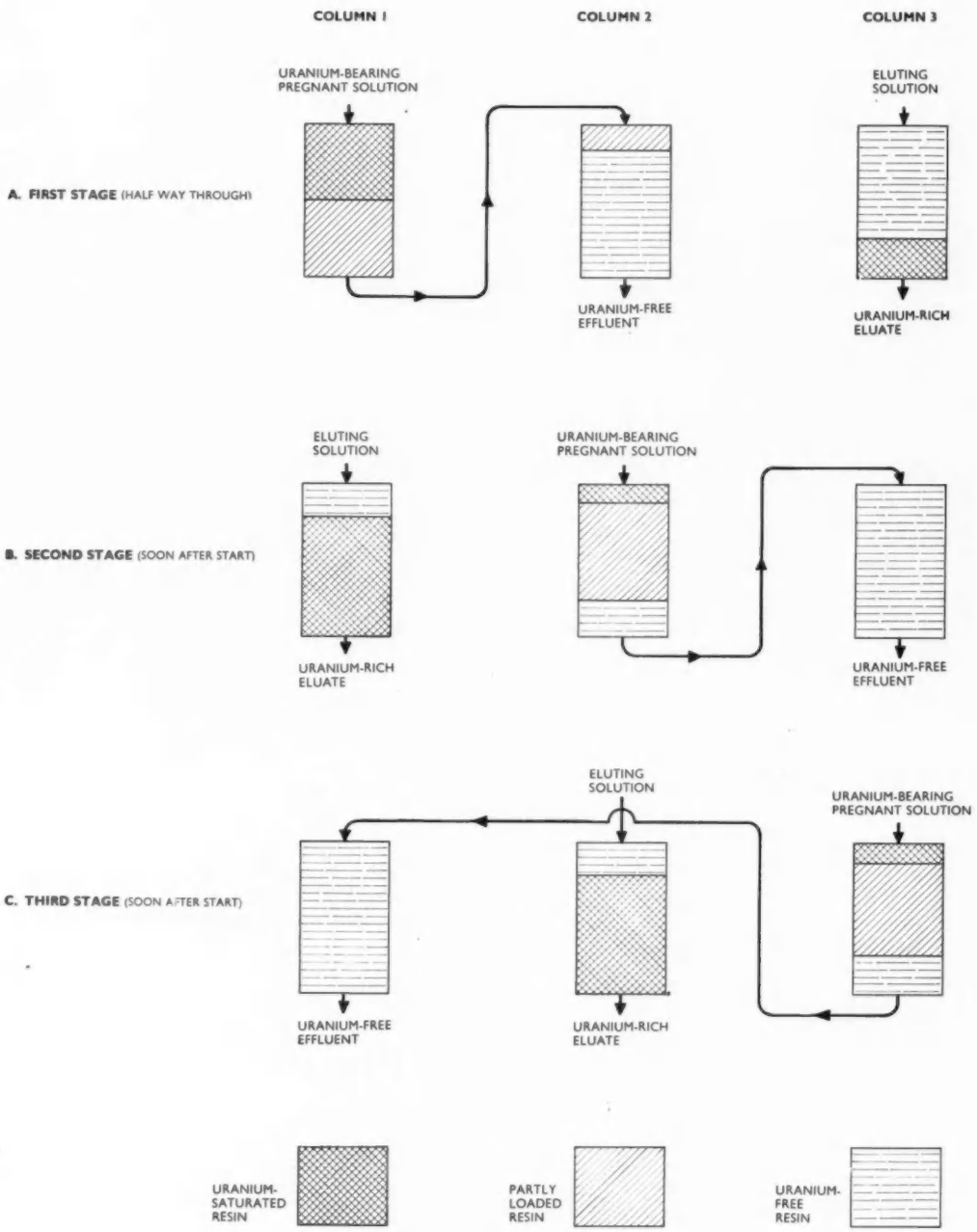


Fig. 7.—Ion-exchange cycle.

afterwards to ensure the complete displacement of the uranium-rich eluate from the column. The eluate, with the uranium as UO_2^{++} and UO_2NO_3, is stored in tanks pending the recovery of its uranium content.

MANGANESE RECOVERY.

The effluent from the ion-exchange columns, containing most of the impurities in the pregnant solution, is normally run to waste, but in some plants it has been found profitable to recover its manganese content for re-use. The pH of the solution is first raised to 4·5 by adding lime to precipitate the iron, aluminium, and colloidal silica. After settlement, the solution is decanted off and the pH is raised further to 9, when manganous hydroxide, $Mn(OH)_2$, comes down. The precipitate, in the form of a slurry, is then oxidised to MnO_2 by blowing in air. The dioxide so formed is filtered off and returned to the leaching circuit.

PRODUCTION OF URANIUM OXIDE.

The eluate from the columns has a pH of about 2. In addition to uranyl nitrate it contains a small amount of iron and aluminium compounds from the original pregnant solution with a little colloidal silica. The impurities are partly precipitated with carefully controlled additions of lime up to a pH of 3·5, but complete elimination is not possible because at a higher pH the uranium begins to come down. The precipitate is therefore filtered off at this stage, and the uranium is then brought down with ammonia at a pH of 6·5 to 7 as a bright orange precipitate consisting of a mixture of the hydroxide $UO_2(OH)_2$ and ammonium diuranate, $(NH_4)_2U_2O_7$. Most of the remaining impurities also come down with it. It is partially dewatered and pumped as a slurry into 15-ton tank trailers, which are taken by road to a central calcining plant for conversion to uranium oxide. The central plant is a virtual necessity, as the final operation has to be carried out by skilled staff in conditions of meticulous cleanliness and it would be uneconomical to put down an installation for the purpose on every mine.

At the calcining plant the slurry is pumped into storage tanks in order that the production of each mine can be sampled and handled separately. From the tanks it is pumped to a filter for dewatering, and the damp filter cake is moulded through an extruding machine into pellets. These are dried and calcined to the oxide U_3O_8 in a slow-speed rotating kiln furnace, coming out as irregular dark greenish-brown granules. The decomposition products—ammonia, nitrogen and water vapour—are volatile and disappear up the stack.

The calcined granules are sampled, loaded into drums and sealed. The oxide then becomes the property of the Union Government, which has the right to purchase all fissile material, and its disposal is out of the hands of the producing mines.

ACKNOWLEDGMENTS.

The author is indebted to the South African Chemical Institute and the South African Institute of Mining and Metallurgy for much published information contributed by the mining groups of the Transvaal and Orange Free State and by the Government Metallurgical Laboratory, Johannesburg. The leaching plant illustration was kindly supplied by the Transvaal and Orange Free State Chamber of Mines and that of the filtering plant by New Consolidated Goldfields Ltd. He would like to express his thanks to the Permutit Co. Ltd., London, for help with the section on the ion-exchange process and for the illustration of one of its plants.

The Witton Network Analyser

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INTRODUCTION.

THE network analyser recently commissioned at the Witton Works is of exceptional interest in that it is the first full-sized analyser in the world to operate on the transformer analogue principle as distinct from the miniature component type of model network assembly used on "conventional" analysers. The new analyser (fig. 1) is available for use both within the Company and outside, and is being employed for power system and general circuit analysis, the solution of polynomial equations, matrices and complex problems of machine design, and for investigations into the frequency response of closed-loop control systems.

Analysers operating on the transformer analogue principle are considerably more versatile than conventional analysers, which are not readily able to simulate the type of physical component required in many intricate system and machine-design problems. A further advantage is that the transformer analogue analyser possesses a high inherent accuracy of the order of 0·1 per cent. Before describing the new equipment in detail, it will be of interest to trace the origin of the design and give an elementary explanation of the method of operation.

Fig. 1.—The Witton Network Analyser.

DEVELOPMENT.

The transformer analogue principle first attracted wide interest in 1937 when Mr. C. L. Blackburn showed how two transformers with three windings on each could be used to simulate complex quantities. A small analyser operating in this manner was built in Newcastle in the same year, and a second analyser was later built at the Imperial College of Science. In these equipments "ideal" voltage transformers were used to represent the impedance of the resistors, inductors and capacitors in a network, and a brief description of the theory of this method is given below.

In the simple case of the analogue with Ohm's law $E=R\times I$, a voltage V_1 applied to the primary of an "ideal" transformer will result in a secondary output voltage of $V_2=V_1\times\frac{T_2}{T_1}$ where $\frac{T_2}{T_1}$ is the turns ratio of the transformer. If the tappings on the secondary winding are adjusted so that the turns ratio is numerically equal to R, then the output voltage will be given by $V_2=R\,V_1$. If the secondary voltage V_2 is made proportional to E in the original equation, the primary voltage V_1 now becomes proportional to I. Thus the transformer can be used to solve the equation $E=R\,I$ on the analogue principle.

A complex quantity such as impedance is simulated by a pair of "ideal" voltage transformers in the following manner :

If a voltage $V+jV'$ is applied to an impedance $Z=R+jX$, then $V+jV'=(R+jX)\quad(I+jI')$

and $V=IR-I'X$

$V'=IX+I'R$

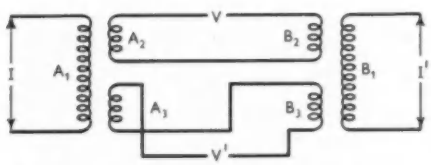


Fig. 2.—Two "ideal" transformers interconnected to simulate a complex quantity.

If the transformers are interconnected as shown in fig. 2 and the turns ratios A_2/A_1 and A_3/A_1 of the windings on the first unit are made equal to R and X respectively, then a voltage equivalent to I applied to winding A_1 will result in voltages equivalent to IR across A_2 and IX across A_3.

Similarly if the turns ratios B_2/B_1 and B_3/B_1 of the second transformer are made equal to X and R respectively, then a voltage equivalent to I' impressed across B_1 will result in voltages $I'\,X$ across B_2 and $I'\,R$ across B_3.

If windings A_3 and B_3 are connected in series then the resultant voltage $IX+I'R$ will be equal to V' and similarly if windings A_2 and B_2 are connected in series subtractively, the resultant voltage $IR-I'X$ will be equal to V. Thus a unit consisting of two transformers with suitable cross connections can be made analogous to impedance, and a number of units can be connected in series and parallel to represent a network. In practice it is often convenient to represent loads by admittances rather than impedances and this is readily achieved by interchanging the input and output coils of the transformers. The normal tapping range of 0 to 1·999 in steps of 0·001 is by this means changed to a tapping range of $\frac{1}{0\text{ to }1{\cdot}999}$, so that every unit has a range from zero to infinity.

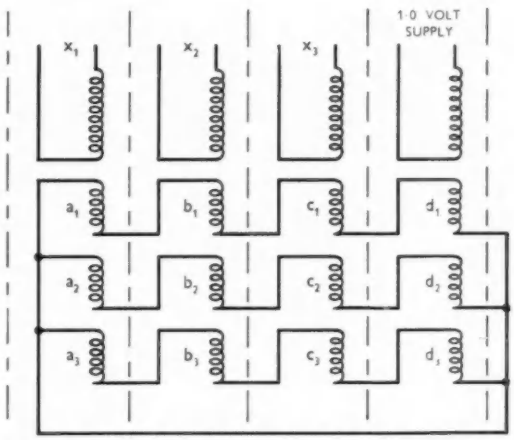


Fig. 3.—Connections of four "ideal" transformers used for the solution of simultaneous equations.

The analyser can also be used for the solution of linear simultaneous equations ; for example a group of three equations can be solved by the use of four "ideal" transformers with appropriate cross connections. If the equations are expressed in the form :

$$a_1\,x_1+b_1\,x_2+c_1\,x_3+d_1=0$$
$$a_2\,x_1+b_2\,x_2+c_2\,x_3+d_2=0$$
$$a_3\,x_1+b_3\,x_2+c_3\,x_3+d_3=0$$

they can be represented by four transformers as shown in fig. 3. In each transformer the secondary windings are adjusted so that the turns ratios are numerically equal to the constants a_1, a_2, a_3, etc.

If a voltage of 1·0 per unit is applied as shown in the diagram and the voltages V_1, V_2, V_3 across terminals X_1, X_2, X_3 measured, then $V_1=x_1$, $V_2=x_2$ and $V_3=x_3$.

With the Blackburn development it is possible, by doubling the number of transformers, to include in-phase and quadrature components so that the matrix can deal with complex numbers and coefficients. This is a very useful feature, since many problems other than those of electrical circuits can conveniently be written in matrix form. This standard matrix network can then be employed to obtain a solution and to experiment with different parameters as required.

The commercial disadvantages of the Blackburn analyser were the complications of construction and operation. There were six or eight leads to every one on a conventional analyser and the method of inter-

connection of units was complicated, and bore little relation to the normal interconnections of ordinary networks.

These difficulties, plus the difficulty of readily understanding an analogue network instead of a straightforward impedance network, have been the main reasons why full-size analysers of the transformer analogue type have not previously been built.

DESIGN.

A careful study of the relative merits of all types of analyser showed that the requirements of the Witton Works could best be satisfied by a network analyser operating on the transformer analogue principle, provided that the difficulties of construction and operation could be overcome. This has been achieved in the new analyser, which has a total of 208 universal units, each capable of simulating voltage or current injection in addition to impedance, admittance or other complex quantities occurring in equations. Two units can also be switched together to represent a complex symmetrical or asymmetrical mutual or transformer coupling. This enormous versatility of all components enables the analyser to deal with the most complex type of electrical or mathematical network problem.

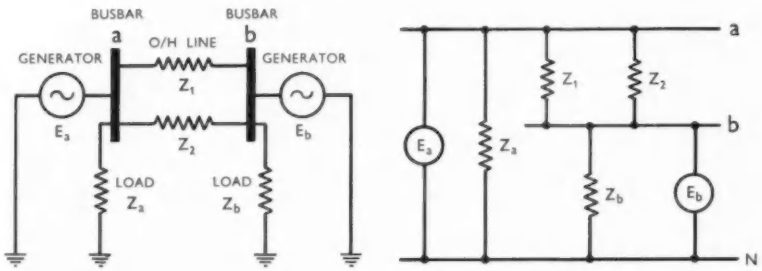


Fig. 4.—(a) System layout and (b) plugging arrangement of simple network.

The difficulties experienced with the Blackburn analyser have been overcome by arranging the leads at each end of a unit into a single multi-core cable which is joined to two plugs on flexible cords at a central plug-board. One plug is used for the "red" end of a unit, and the other for the "green" end. This enables units to be connected in series by plugging the "red" end of one unit into the "green" end of the second unit, or in parallel by plugging the two "red" ends into one busbar and the two "green" ends into another.

This is conventional analyser practice, and enables a full power system network to be built up, with the actual busbars of the system being copied on the plug-board (fig. 4).

For matrix work it has been arranged that the elements of the matrix can be identified with the physical positions of the units in the racks. The column connections are made on the fronts of the units and the row connections are made in busbars on the plug-board. This gives a compact arrangement that is easy to set up and check.

In addition to these improvements to the plugging arrangement, the Witton analyser differs from the earlier models in layout, which has been carefully designed to allow different sections of the analyser to work independently at the same time. As a power system study does not normally monopolise more than three boards, the fourth board is always available for the many general problems which arise in industry. Substantial improvements have also been made to the metering arrangements, including the provision of direct and bridge metering, with facilities for automatic checking and a digital type of display designed to allow a device for the direct printing of results to be incorporated. The metering arrangements enable the operators to use the analyser directly as a conventional machine, no knowledge of the underlying analogue principle being needed.

CONSTRUCTION.

The analyser is built in four individual sections, each section consisting of a central plug-board, fig. 5, with 52 standard analyser units arranged in racks on either side. All 52 units in one section are connected to their plug-board by jumper leads so that the units can be connected together in any way desired. Front sockets are also included in the individual units so that interconnections can alternatively be made here, or a combination of plug-board plugging and front plugging can be used for special problems.

The most formidable task in the construction of the analyser was the great amount of interconnecting and complex switching required. For example, each analyser unit (fig. 6) contains 9 multi-position, multi-wafered switches.

These, together with the compensating circuits and terminal sockets, involve a total of 700 soldered joints for each unit. Thus for the 208 units alone there are a total of 145,600 soldered joints, and apart from these, the interconnecting plugs and plug-board, metering selection plugs and general inter-

connecting leads to the control desk result in a further 50,000 soldered joints.

The design, construction and commissioning of the complete equipment was carried out at the Witton Works ; the wiring of the individual units was undertaken by the G.E.C. Telephone Works at Coventry, who used their well-established techniques of running lists and cable forms.

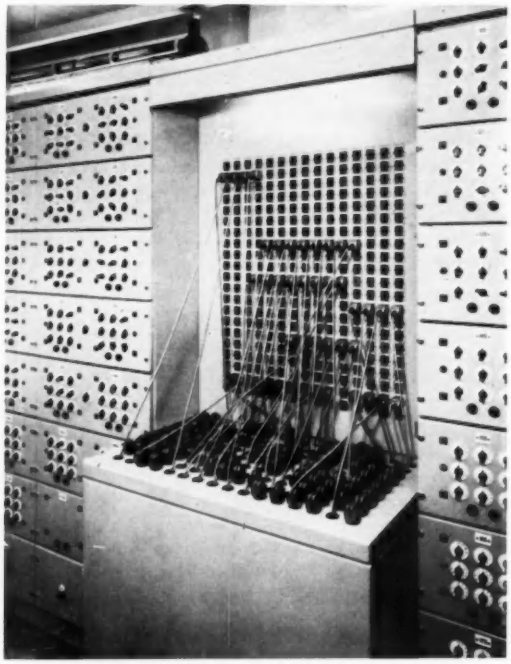


Fig. 5.—A central plug-board

To facilitate the task of wiring the analyser, a special bonded strip of ten different-coloured plastic covered wires has been used for all the leads to the plug-boards, the strips being grouped together and run inside bakelite tubes. This arrangement ensures a neat layout with a minimum of electrical interference. The control and indicating leads are run in standard 61-core telephone-type cable, and the metering leads are channelled in separate screened cables.

The control desk (fig. 7) is of wooden construction and has been specially designed to accommodate to the maximum advantage all control facilities, recording instruments and metering arrangements. Carefully designed interlock and monitoring facilities are incorporated to obviate the possibility of metering or recording errors. Particular care has been taken to group all continuous controls and

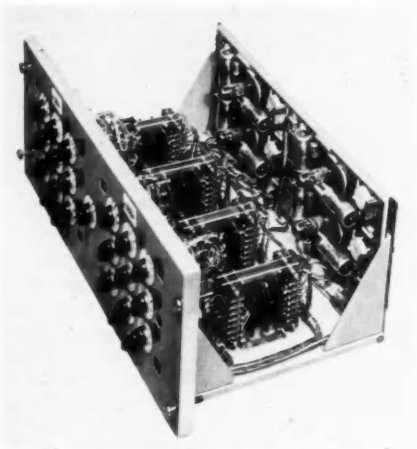


Fig. 6.—A standard analyser unit.

meters within easy reach of the operator, and to provide him with a clear view of the complete analyser. These features play an important part in minimising operational fatigue when extensive system studies are being conducted.

Transformer Compensating Circuits.

As the ultimate accuracy of the analyser depends upon the degree to which the apparent magnetising currents of the transformers can be reduced, an electronic circuit is incorporated which continuously monitors the volts-per-turn on the transformer and injects into a special compensating winding the required magnetising ampere turns.

The overall result is that the currents flowing in the actual transformer analogue network are reduced to a

Fig. 7.—The central control desk.

very small value. The electronic equipment is built on a printed circuit to give simple access, neatness and maximum reliability.

METERING EQUIPMENT.

Two types of metering are employed as follows :

(*a*) *Direct Metering.*

The analogue voltages picked up from the analyser are fed to electronic summating networks which convert the quantities from cartesian co-ordinates into polar form so that the normal power system quantities of volts, amperes, watts and vars can be displayed on conventional indicating instruments scaled in " per unit " quantities (fig. 8). For the ammeter and voltmeter, scales ranging from 0·1 to 31·6 per unit in multiples of $\sqrt{10}$ can be selected by means of switches. The range of the wattmeter and var-meter is the product of the ranges selected for the ammeter and voltmeter, and is automatically computed and displayed on an illuminated unit.

(*b*) *Self-balancing Bridge Metering.*

This equipment consists of four independent self-balancing bridge units metering the two cartesian co-ordinates of the voltage and current at the required point, and gives an illuminated in-line number display of the results. Each meter consists basically of a reference transformer, the output voltage of which is varied by automatic tapping switches which run until the output voltage exactly balances the input voltage being metered. An electronic error-detector measures the unbalance voltage and sends the required signal to the three switches which automatically tap the reference transformer. The average time for a balance is approximately 2 seconds, and the equipment gives an accuracy of 0·1 per cent, or 0·001 per unit of base.

CONTROL AND MONITORING ARRANGEMENTS.

The control desk is arranged in two halves which house the direct metering and bridge metering respectively, and control switches make it possible to couple any of the four plug-boards to either metering system. Unit selection buttons are provided so that any unit can be metered, and it is possible to select for metering the voltage from either end of the unit to neutral, or the voltage across the unit.

Each half of the control desk has an illuminated plotting table which has a small square corresponding to each socket of the plug-board, and recording sheets are prepared to fit over these plotting tables. When a unit is selected for metering, the square involved on the plotting table is illuminated, and the readings can be directly recorded in the correct place on the covering recording sheet.

PERFORMANCE.

When used for circuit analysis the Witton analyser can deal with any size of steady-state circuit calculation up to a maximum of 208 complex impedance units of the form $(\pm R \pm jX)$. In general equation work, solutions of complex and non-complex matrices are possible, and a matrix inversion can readily be obtained.

The steady-state and stability behaviour of any large power system can be fully investigated and the busbar voltage levels and power distribution determined. The effects of alterations and additions to transmission networks can be predicted, and means of reducing system losses assessed. The analyser can also be used to calculate synchronous capacitor ratings or tap-changing transformer requirements and to determine the optimum location for additional generating plant, interconnections and feeders.

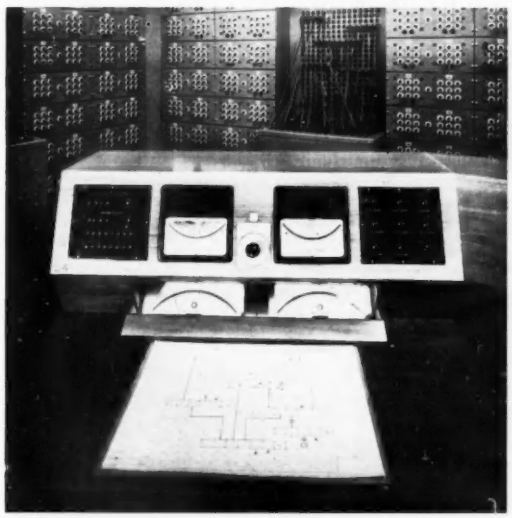


Fig. 8.—The direct metering section of the control desk.

For problems associated with the design of rotating machines the direct or quadrature axis equations can be used, and equivalent circuits can be arranged to allow the physical picture of the machine to be retained and to provide direct adjustment of any required machine parameter. The analyser can also be used to solve any non-electrical analogue problems that can be represented by steady-state equations or circuits. Typical examples are calculations concerned with the critical speeds of rotating shafts, heat flow, and framework stress analysis.

Diesel-electric Locomotives for British Railways

By J. C. TURRALL, A.M.I.E.E., and W. E. LEWIS, A.M.I.E.E.,
Traction Department, Witton.

Fig. 1.—N.B.L.-G.E.C. Type 1 diesel-electric locomotive.

SHORTLY after the modernisation plan for British Railways was published in 1955, the British Transport Commission announced a programme for the construction of diesel locomotives of four power classifications to cover the range of 750 to 2,400 h.p. in the following steps :

Type 1	750—1,000 h.p.
Type 2	1,000—1,250 h.p.
Type 3	1,500—1,700 h.p.
Type 4	2,000—2,400 h.p.

Among the orders received by the G.E.C. in connection with the above was one for the complete power equipments, including the diesel engines, of ten Type 1 locomotives to be built by the North British Locomotive Co. Ltd. Some of these locomotives (fig. 1) are now in service and are based on Stratford Motive Power Depot in the Eastern Region of British Railways. They are intended mainly for the haulage of medium-weight freight trains, such as those transferring traffic between marshalling yards in the London area, and can also be used on light passenger trains when steam heating is not required. No heating boiler is provided, but steam pipes are fitted so that steam can be piped through from another type of locomotive to the coaches of a passenger train when running in multiple.

MECHANICAL DESIGN.

The locomotive is a single-cab design with bonnet superstructure and the Bo-Bo wheel arrangement. An engine-generator set comprising a Paxman 16YHXL 800 h.p. engine direct-coupled to G.E.C. main and auxiliary generators is housed in the two compartments of the bonnet forward of the cab. The generator compartment also houses a bulkhead-mounted vane motor and oil valves for automatic control of the

generator output, roof-mounted generator field resistors, a motor-blower feeding Nos. 3 and 4 traction motors, and a traction equipment cubicle. A motor-blower feeding Nos. 1 and 2 motors, a compressor set and resistor, engine speed-setting valves, and local start/stop pushbuttons are mounted in the engine compartment. Ahead of this is the radiator compartment, with cooling fan. The arrangement described is illustrated in the drawing (fig. 2).

The single cab accommodates controls arranged for operation from either side, so that manipulation is equally convenient in both directions of travel. Traction motor field diversion resistors are mounted forward of the cab on platforms which run the length of the central compartments. Two battery boxes mounted under the platform each contain half the 110 V battery and a battery isolating switch.

A short end compartment behind the cab contains two exhauster sets, mounted one above the other, the exhauster field divert resistors, a driver's cooker, and an auxiliary control equipment cubicle which is accessible through hinged doors opening into the cab.

Fixed end electrical couplers of the butt contact type are fitted to the headstocks for multiple-unit working. Handlamp sockets are provided at various points on the locomotive to facilitate inspection. Principal details of the locomotives are tabulated below :

Wheel arrangement	Bo-Bo
Maximum speed	60 m.p.h.
Maximum tractive effort	42,000 lb.
Continuous rated tractive effort	20,000 lb.
Wt. in working order	68 tons
Length over buffers	42 ft. 6 in.
Overall width	8 ft. 8½ in.
Overall height	12 ft. 6 in.
Bogie wheelbase	8 ft. 6 in.
Bogie pivot centres	20 ft. 0 in.
Wheel diameter	3 ft. 7 in.

DIESEL ENGINE.

The 16-cylinder vee-type diesel engine (fig. 4) is set to give a continuous traction output of 800 b.h.p. at 1,250 r.p.m. Two pressure chargers are fitted, one for each bank of cylinders. The camshaft-operated individual fuel pumps receive a supply of fuel under positive pressure from a gear type boost pump. To remove the risk of contamination of engine lubricating oil by fuel leakage, the fuel pumps and fuel pump camshaft have a separate lubrication system with its own sump, pump, and strainer.

Forced lubrication of the engine is by means of a main pressure pump working in conjunction with a second pump for passing oil at low pressure through the oil section of the radiator. Oil flow through the radiator is regulated by an independent relief valve which can be adjusted to suit local conditions. The engine cannot be started until a motor-driven priming pump has built up sufficient pressure to draw the fuel bar to the starting position and close a pressure-switch in the pipe line to the bearings.

The engine speed-setting system is based on the action of three oil-operated pistons on a triangular plate. The height of a point near the centre of the plate varies according to the number of pistons operated and their positions. By transmitting the movement of this point to the governor reset valve by a simple system of levers and a push rod, eight engine speed settings are obtained.

ELECTRICAL EQUIPMENT.

The main generator, with its overhung auxiliary generator, is carried on an extension of the engine under-bed, so that the whole of the engine-generator set forms a compact and rigid unit. A coupling flange is provided at the driving end of the generator, through which the armature is solidly bolted to the engine crankshaft flange.

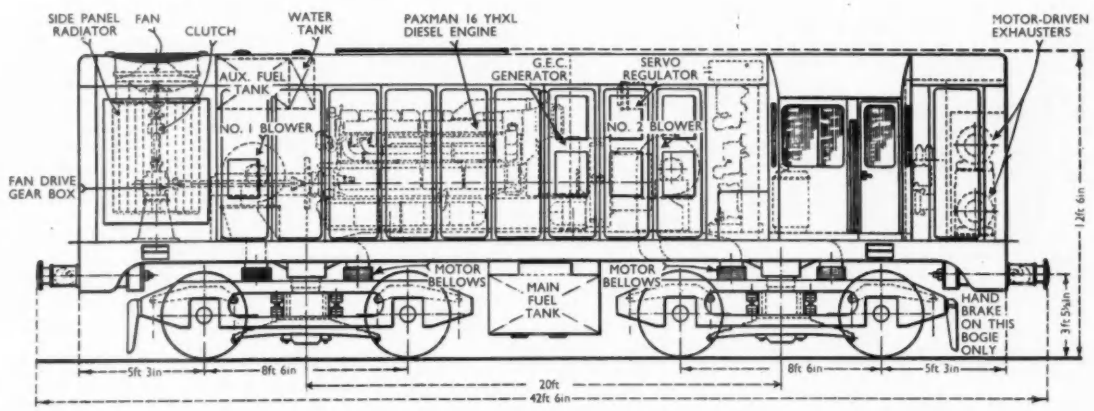
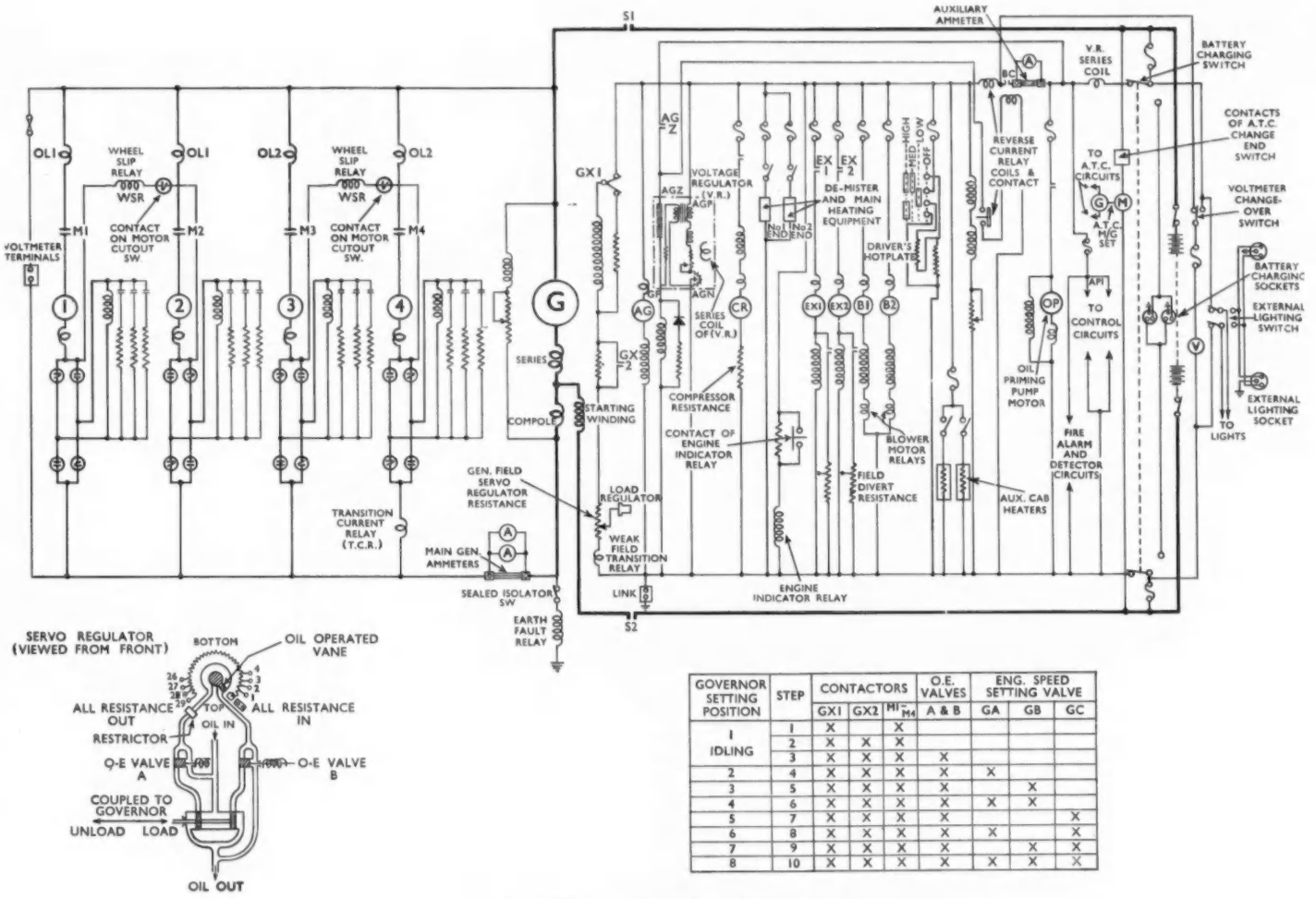


Fig. 2.—General arrangement of locomotive and principal dimensions.



GOVERNOR SETTING POSITION	STEP	CONTACTORS			O.E. VALVES	ENG. SPEED SETTING VALVE		
		GX1	GX2	M1~M4	A & B	GA	GB	GC
1 IDLING	1	X		X				
	2	X	X	X				
	3	X	X	X	X			
2	4	X	X	X	X	X		
3	5	X	X	X	X		X	
4	6	X	X	X	X	X	X	
5	7	X	X	X	X			X
6	8	X	X	X	X	X		X
7	9	X	X	X	X		X	X
8	10	X	X	X	X	X	X	X

Fig. 3.—Main power and auxiliary schematic diagram
Type 1 diesel-electric locomotive.

An extension to the main generator shaft carries the auxiliary generator, the total weight of the two armatures being carried partly by the bearing between them, in the main generator end-shield, and partly by the outboard engine crankshaft bearing. The auxiliary armature can be removed complete from the generator shaft extension without disturbing the windings.

A fan mounted on the driving end of the main generator armature hub draws ventilating air partly through the auxiliary generator, and partly through protected vents in the bearing housing. After passing in parallel paths through the armature core and over the periphery of the armature and field coil surfaces, the air is exhausted into the engine compartment.

Current is supplied from the main generator to four axle-hung, nose-suspended traction motors connected in parallel. Two motors are mounted in each bogie and drive the axles through Wiseman solid gearwheels. Forced ventilation is provided by two motor-blower sets, each serving the traction motors of one bogie. Grease-lubricated roller bearings are used for both armatures and axle suspension bearings.

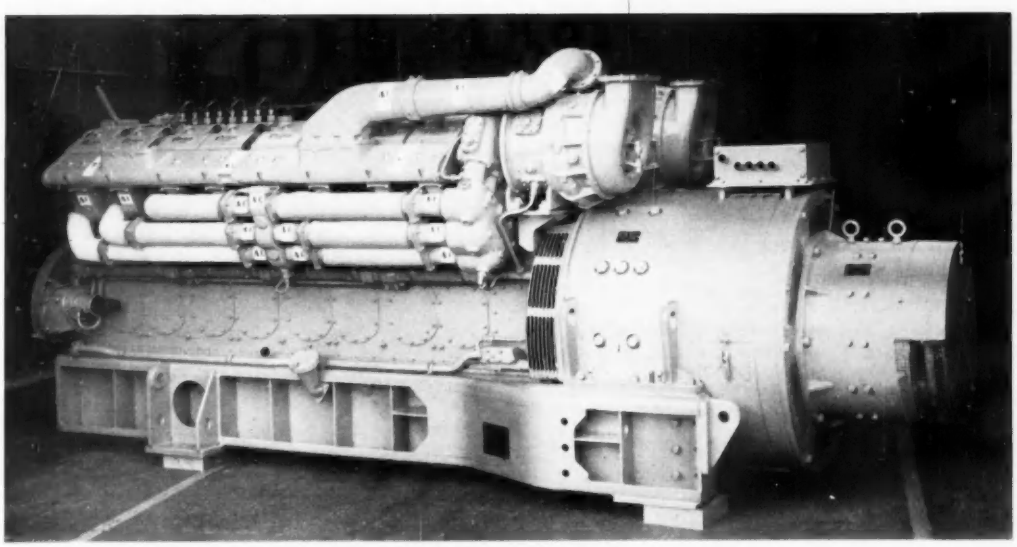


Fig. 4.—Engine-generator set.

CONTROL SCHEME.

The main generator has series, shunt and separately-excited fields, and a series starting winding enabling it to be motored from the battery for starting the engine. Two main electromagnetic contactors connect the 48-cell, 123 amp.-hr. lead-acid battery to the generator for starting purposes. Excitation for the separately-excited field is taken from the auxiliary generator and is controlled by an automatically regulated resistance. The generator separately-excited field is held constant on the first two controller notches, the automatic regulator being brought into action on notch 3.

On notches 1 to 3 the engine speed is constant at 625 r.p.m., after which it is accelerated in steps to a maximum of 1,250 r.p.m. on notch 10. From notches 3 to 10 the automatic field regulator is operative and adjusts the generator excitation so that the engine is fully loaded, but cannot be overloaded, on each notch. The load control system operates through a control valve, actuated by the engine governor, which admits oil to a vane motor driving a brush round the circumference of a stationary commutator with its segments connected to the various sections of the regulating resistance. Two oil-electric valves connected in the feed pipes to the vane motor override the automatic control during the "off" position and the first two steps of controller operation.

The four traction motor circuits are controlled by individual electro-pneumatic contactors and overload relays, the contactors being capable of handling possible fault conditions. Relay settings are chosen so that protection is also given to the generator, while allowing the maximum designed tractive effort to be developed by the traction motors. Two cam-operated electro-pneumatic reversers, connected on the negative side of the generator supply, each control two traction motor fields.

The continuous rating of the motors in full field corresponds to a locomotive speed of 11 m.p.h. on full power. The locomotive develops a maximum

tractive effort of 42,000 lb., which corresponds to 27·6 per cent of the adhesive weight. Maximum speed is 60 m.p.h.

An advanced degree of motor field weakening is provided by three steps of field diversion. The steps are taken automatically, one at a time, in the appropriate conditions under the control of a transition relay in the generator field circuit, operating in conjunction with the automatic field regulator in such a way that the motor weak-field contactors do not close until the generator excitation and voltage have been adjusted to the correct values. Backward transition is also fully automatic, and is initiated by a current relay in one motor circuit when a sufficient increase in load is demanded from the generator, such as that caused by an increase in track gradient.

Further protection is given to the power circuits by earth fault and wheel slip relays.

A main ammeter indicating the continuous rating of the equipment, and the zone in which high tractive efforts are developed, is provided at each driving position in the cab. Both instruments are connected to a common shunt.

Fig. 6.—One of the duplicate driving positions.

CAB-CONTROLS.

Two master controllers are mounted in the cab (fig. 6) so that the driver can be seated at either side according to the direction of travel. Each controller has two handles which are permanently in position, one controlling the power shaft and the other the selector shaft. The latter has four positions, namely "Off", "Engine Start", "Forward" and "Reverse". There is no electrical feed to the controller until the control switch key has been inserted and turned to "On". Insertion of a master locking key then unlocks the controller, enabling the selector shaft handle to be turned to "Engine Start", when operation of the "Engine Start" pushbutton causes the generator to be motored from the battery as described already. When the auxiliary generator voltage rises to the value required for connecting it to the battery, the closing of the battery contactor by the operation of its associated reverse current relay opens the pushbutton circuit through an interlock, so that it is impossible for the driver to continue motoring the main generator after the engine has run up to idling speed.

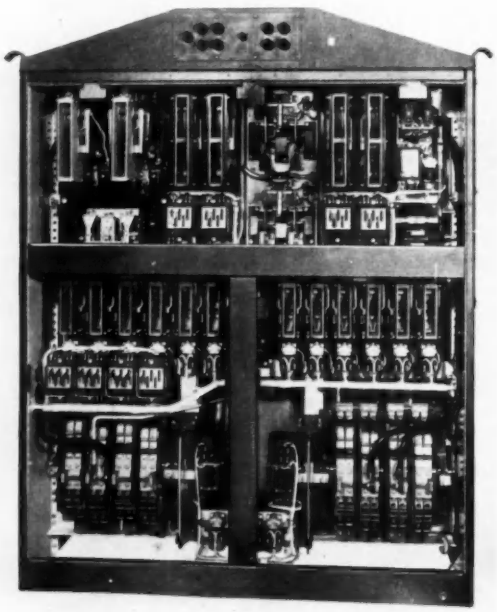


Fig. 5.—Main equipment cubicle.

To move the locomotive, the selector shaft handle is set at "Forward" or "Reverse", and control is carried out by manipulation of the power shaft handle. The power shaft contacts control the motor circuit contactors, the engine governor speed-setting valves, the oil servo control valves, the operating coils of the generator field control contactors, and other circuits required for operating in multiple with locomotives equipped by other manufacturers.

Sanding pedals are provided at each driving position for operating sanding gear arranged for either direction of running.

AUXILIARY SERVICES.

Auxiliary circuits are supplied at 110 V d.c. from the auxiliary generator, the voltage being controlled by a carbon pile voltage regulator. The auxiliary control equipment cubicle is shown in fig. 7.

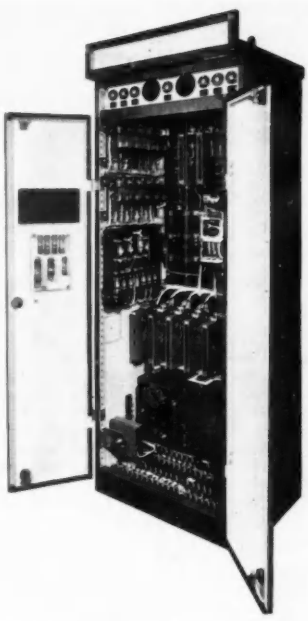


Fig. 7.—Auxiliary equipment cubicle.

A motor-driven compressor, controlled by a contactor, provides compressed air for the electro-pneumatic control equipment and locomotive brakes. Two motor-driven exhausters provide for the operation of vacuum-braked trains. The exhauster motors have a step of field diversion to give a higher running speed for rapid brake release. Two motor-driven blowers supply cooling air for the traction motors. There is a relay coil in each blower motor circuit, so that in the event of a motor failure contacts are released which short-circuit a resistance in series with an indicator lamp, causing the lamp to brighten and so signal the fault in the cab. A similar form of warning is given of motor overloads, wheelspin, earth faults or high water temperature, and is accompanied in these cases by automatic reduction of engine speed to idling. Low water level and low lubricating oil pressure cause the engine to be shut down. Fire warning is given by a firebell operated through a relay in the fire-detection system.

The control circuits are fed from the battery. A key-operated control switch at each driving position controls the feed to the dead man's pushbuttons and pedals, the master controller, and braked/unbraked changeover switch. Automatic train control equipment is provided in the driving cab, the change-end switch having a contact in each positive feed to the master controllers to ensure that the locomotive cannot move off until the A.T.C. equipment is made operative.

Lighting circuits, fed at 110 V, are taken directly off the battery through a double-pole isolating switch. Battery charging and external lighting supply sockets are connected to their respective circuits through changeover switches, enabling external supplies to be used for these services when required.

TECHNICAL LITERATURE

A digest of recent articles and papers by members of the G.E.C. and its associated companies

STRUCTURAL AND ELECTRICAL PROPERTIES OF SILVER NIOBATE AND SILVER TANTALATE (733).*

By M. H. Francombe and B. Lewis (Research Laboratories).

Acta Crystallographica, Vol. 11, *pp.* 175-178, *March*, 1958.

At room temperature both $AgNbO_3$ and $AgTaO_3$ possess orthorhombic multiple-cell perovskite-type structures and are isomorphous with $NaNbO_3$. In $AgNbO_3$ the structure changes sharply to near-tetragonal at 325 deg. C., while in $AgTaO_3$ a similar change occurs, more smoothly, at about 375 deg. C. At higher temperatures a sequence of structural changes closely similar to that in $NaNbO_3$ leads to a fully isotropic condition at 560 deg. C. for $AgNbO_3$ and 480 deg. C. for $AgTaO_3$.

The permittivity of $AgNbO_3$ shows a peak at the orthorhombic-tetragonal transition reminiscent of that normally observed at a ferroelectric or antiferroelectric Curie temperature. Weak hysteresis and pyroelectric effects indicate a low value of spontaneous polarisation. It is concluded that in $AgNbO_3$ the structural changes are probably influenced chiefly by ionic packing considerations. With $AgTaO_3$ the presence of free silver precluded electrical measurements, but the nature of its structure transitions and the permittivity data obtained for the solid solution $AgNb_{0\cdot75}Ta_{0\cdot25}O_3$ suggest the absence of ferroelectricity.

SUBJECTIVE VISUAL EFFECTS OF A.N.T.S.C. COLOUR TELEVISION RECEIVER TOLERANCES (739).*

By P. S. Carnt and G. B. Townsend (Research Laboratories).

Optica Acta, Vol. 5, *Special Number*, 1958.

The variations in receiver performance which viewers will accept in colour television have been investigated for the more important parameters which colour adds to the domestic receiver, i.e. effects due to reference oscillator phase, chrominance signal gain, and the background controls of the three-gun colour tube. These tolerances are expressed in engineering and colorimetric terms and the correspondence with viewers' reaction is given on a subjective scale. The experiments were devised to simulate domestic viewing, and the variations which typical audiences will accept are compared with those which the trained observer can distinguish under critical conditions. The influence of receiver performance on the choice of normalising illuminant is discussed.

THE ELECTRICAL CONDUCTIVITY AND THERMOELECTRIC POWER OF BISMUTH TELLURIDE (759).*

By H. J. Goldsmid (Research Laboratories).

Proceedings of the Physical Society, Vol. 72, *pp.* 633-646, 1958.

The electrical conductivity and thermoelectric power of the semi-conductor Bi_2Te_3 have been measured between 150 deg. K. and 300 deg. K. *n*-type and *p*-type samples with a wide range of carrier concentration have been included. Most samples have shown extrinsic conduction and have been partially degenerate over at least part of the temperature range, so it has been necessary to use Fermi-Dirac statistics in interpreting the results. A few samples have exhibited mixed and intrinsic conduction at the higher temperatures. It has been possible to determine the variation of carrier mobility with temperature and to estimate the energy dependence of the relaxation time, as well as a number of the semiconductor parameters.

HEAT CONDUCTION IN BISMUTH TELLURIDE (761).*

By H. J. Goldsmid (Research Laboratories).

Proceedings of the Physical Society, Vol. 72, *pp.* 17-26, 1958.

The Lorenz number of the semiconductor Bi_2Te_3 has been evaluated, for the range of partial degeneracy, from data provided by the measurements of electrical conductivity and thermoelectric power. The calculated electronic component of the thermal conductivity, for *p*-type material, has been found to agree with the experimental results, assuming the lattice thermal conductivity to be independent of the electrical conductivity. Agreement has also been obtained for non-halogen-doped *n*-type Bi_2Te_3, but not for halogen-doped material. It has been shown that the reason for this is the high effective scattering cross-section, for phonons, of the halogen atoms.

The theory of the transport of ionisation energy has been found to agree very closely with experiment.

TRIODES AND TETRODES FOR U.H.F.-S.H.F. OPERATION.

By C. A. Tremlett and A. D. Williams (Research Laboratories).

Electronic Engineering, Vol. 30, *pp.* 335-340, *May*, 1958.

This review deals briefly with the advances over the last ten years in the development of space charge control valves for operation above 300 Mc/s. The improvements in technology are described with particular reference to some valve types. Two tables are included, the first giving data on valve geometry, the second summarising general information (static characteristics, r.f. performance, etc.) regarding a wide selection of valves.

PHOTOCONDUCTIVITY (766).*

By D. A. Wright (Research Laboratories).

British Journal of Applied Physics, Vol. 9, *pp.* 205-214, *June*, 1958.

The basic factors influencing photoconductivity are first discussed, and the general pattern of behaviour to be expected is indicated. The preparation and properties of cadmium sulphide are then dealt with in some detail. Other photoconducting compounds are described more briefly, and it is shown that their properties also fit into the general pattern. Following a discussion of the nature of the impurities and defects in the crystal lattice which influence the sensitivity, the applications of photoconductors are outlined briefly.

*** A limited number of reprints is available of those papers marked with an asterisk. Copies may be obtained on application to the Editor, G.E.C. Journal, Magnet House, Kingsway, W.C.2.**